STOCHASTIC FOREST GROWTH

SIMULATION:

INCORPORATING GROWTH PREDICTION UNCERTAINTY WITH WIND AND FIRE DAMAGE INTO CARBON SEQUESTRATION ESTIMATES AND DISCOUNTED CASH FLOW ANALYSIS

A thesis submitted in partial fulfilment of the requirements for the

Degree

of Master of Forestry Science

at the University of Canterbury

by Leslie. J. Dowling

New Zealand School of Forestry,

2015

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Acknowledgments

The author wishes to express sincere appreciation to Professor Bruce Manley and Dr David Evison for their assistance in the preparation of this manuscript. The education received by the author during the process of this research is a testament to their knowledge and teaching.

I would also like to acknowledge Timberlands Ltd for access to their forest information, and to Scion for supporting me with assistance both in the office and in the field collecting data. I would like to thank Rayonier for letting me into their forest estate during a testing time following the 2013 Canterbury wind storms. Finally, I would like to acknowledge the kindness and supportive nature of my colleagues at Scion who have helped along the way; in particular I would like to thank Mark Kimberley and David Henley.

Abstract

Uncertainty in forest productivity prediction and the variable reduction from wind and fire damage makes predictions of forest Net Present Values (NPVs) and carbon sequestration uncertain, creating a distribution of possible future outcomes for new forestry investments. To quantify the distribution of NPV and carbon sequestered at harvest a stochastic modelling system was used incorporating uncertainty around the expected site productivity of radiata pine (Pinus radiata D. Don) (Palmer, Hock et al. 2009) with the influence of catastrophic wind and fire damage (Moore, Manley et al. 2011, Anderson, Doherty et al. 2008). By combining uncertainty in forest productivity estimation with that of volume reduction from catastrophic damage this system captured a complete picture of potential forest growth outcomes for forest volume and carbon sequestration.

The stochastic forest modelling system used repeated runs of the 300 Index growth model (Kimberley, West et al. 2005) inside the Atlas Forecaster forest modelling software (Snook 2010). Site Index and 300 Index values were used to calibrate the model to site productivity. They were generated using the R statistics package (R Core Team 2012) with means, variances and correlation based on the sampled uncertainty of spatially modelled productivity estimates referenced against measured PSP data. The generated productivity indices were used to construct Forecaster project files which were used to initiate model runs. Simulated stem volume and stocking from forest growth simulation were used to calculate the likelihood of wind damage (Moore and Quine, 2000) for catastrophic damage simulation. The simulated average probability of damage was calibrated to match the surveyed regional average rates of wind and fire occurrence in Moore, Manley et al. (2011) and Anderson, S. A. J., et al. (2008) respectively. Growth simulations selected for damage were modified to represent salvage harvest operations and re-run with an earlier harvest matched to the year of the simulated event. Damaged simulations were modified with a higher proportion of logging waste and NPV calculations using increased logging costs. The NPVs and total carbon sequestered for the collated final simulations were used to display the likelihood of each simulated outcome.

Results were compared across differing levels of catastrophic damage on high and low productivity sites. The addition of wind and fire damage to NPV estimates lowered the mean NPV especially for high productivity sites. However, the stochastic NPV estimates contained large variation and no statistically significant results were achieved, even with high numbers of repeated simulations. A reduction in total carbon sequestered prior to harvest due to wind and fire of between 3 and 5% was found for the case study forest in the Central North Island of New Zealand. However, there was a large amount of variation in the simulations around these means and the observed reduction was not statistically significant. Confidence intervals for estimates of carbon sequestration without wind and fire damage were between 5% and 10% of the mean, and the addition of wind and fire damage increased variance and confidence intervals to 20% of the mean.

The results and conclusions show the significance of uncertainty for new forest investments on previously un-forested land both in terms of NPV and carbon sequestration. The trend across all scenarios with catastrophic damage is a tailed distribution with the main proportion of outcomes centred on the expected deterministically calculated value, for both carbon sequestered and NPVs. On average NPVs were reduced by $600/ha through the inclusion of average rates of catastrophic damage. However, there was high variation in the result and the predicted reduction is not statistically significant.

Glossary

300 Index: - Both a radiata pine (*Pinus radiata D.Don*) volume growth model and an index to measure site productivity calculated from mean stand volume.

CSV: Comma Separated Value – A simple computer file type where cell values in plain text form are separated by commas.

DBH: Diameter at Breast Height - The diameter at 1.4m above ground on the uphill side of the tree (if the ground is not flat).

ETS: Emissions Trading Scheme – New Zealand's market based system for reducing greenhouse gas emissions to satisfy its commitments under the UNFCCC, where units of carbon dioxide equivalent emissions are traded between emitters and sequesters.

FCP: Forest Carbon Predictor – A spreadsheet based implementation of the 300 Index forest growth model.

GUI: Graphic User Interface - the visual method by which computer software interfaces with humans, using windows icons and menus.

LENZ: Land Environments of New Zealand - a classification of New Zealand environments done by Landcare Research (Leathwick, Wilson et al. 2003).

MTH: Mean Top Height - The height predicted by the Petterson height/DBH curve for a DBH corresponding to the quadratic mean DBH of the 100 largest trees per hectare (based on DBH) in a stand.

PSP: Permanent Sample Plot – A known area of forest which is repeatedly measured over time to monitor diameter and selected representative tree heights.

QGIS: Quantum Geographic Information Software - the open source GIS software package used for mapping in this thesis (QGIS Development Team 2013).

R: A statistical computing environment. R is one of the statistics software packages used for this research (R Core Team 2012)

SAS: Statistical Analysis System – Analytics software for business intelligence, data management and predictive analytics. SAS is one of the statistics packages used for this research.

Site Index: A measure of site productivity calculated from tree height growth

Stochastic: Random in nature, from a probability distribution or pattern that can be analysed statistically but not predicted precisely.

UNFCCC: United Nations Framework Convention on Climate Change – An international treaty to cooperatively consider what they could do to limit average global temperature increases and the resulting climate change, and to cope with whatever impacts were, by then, inevitable[1]. New Zealand is signatory to this treaty.

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[1] Background on the UNFCCC: The international response to climate change. Online reference [accessed 18/03/2015] http://unfccc.int/essential_background/items/6031.php

Chapter 1 - Introduction

New Zealand has agreed to a series of targets to reduce emissions of carbon dioxide as a mitigation strategy to climate change under the United Nations Framework Convention on Climate Change (UNFCCC). Forests play a critical role in the New Zealand's climate change strategy reducing New Zealand's emissions by sequestering carbon during photosynthesis as part of the wood formation process, and therefore reducing carbon dioxide in the atmosphere. To encourage forest growers to plant trees for carbon sequestration and penalise carbon emitters New Zealand uses the Emissions Trading Scheme (ETS), where units of carbon dioxide are traded between sequesters and emitters at a market determined value. The price of carbon sequestration units forms the incentive for participants in the ETS to reduce carbon emissions. For forest owners acquiring carbon sequestration credits to trade forms part of a forest investment. This study aims to reduce uncertainty for investment in forests aiming to create revenue through carbon sequestration.

Many factors affect forest growth and economic returns. While the main source of economic return in New Zealand forestry is from the sale of logs, more recently the sale of carbon sequestration credits also contributes to forest profitability. With this additional revenue stream forest growers face uncertainty in the price of carbon sequestration in addition to the usual growth and marketing uncertainty for log sales. The price of carbon sequestration is subject to the volatile ETS carbon market and changing government policy. Due to the many factors affecting the quantity and price received for forest products the probability that forest returns will match predicted a predicted revenue stream is slim. The effects of risk and uncertainty are such that values can be higher or lower than expected, creating the distribution of likely investment returns.

Forest volume is a key driver of profitability for both log revenue and carbon sequestration. This research looks at uncertainty in forest growth predictions and how this affects forest value and total carbon sequestered. It will draw conclusions on the level certainty possible for Net Present

Value (NPV) and carbon sequestration estimates for those planning a new radiata pine *(Pinus radiata D. Don*) investment plantation forest in New Zealand. The analysis uses stochastically generated forest productivity values to model forest growth and then applies catastrophic damage to those simulations to find the distribution of probability for forest returns and weight of carbon dioxide equivalents sequestered as carbon.

Uncertainty in volume prediction was separated into two categories; error in productivity index estimates and the variable reduction in volume due to catastrophic damage. Error in productivity index estimates represents the normal variation around the expected rate of forest growth due to many factors causing minor damage such as soil nutrition, water availability and biological attack. This variation can be sampled by comparing modelled estimates of forest productivity with measured forest growth. Variation from catastrophic damage is the reduction in forest volume accountable to wind and fire damage severe enough to justify abandoning the tree crop. The likelihood of occurrence and effects on volume production were calculated from past examples of catastrophic events and applied to forest growth simulation. To ensure that measures of productivity prediction error and likelihood of catastrophic damage were exclusive and could be measured and simulated separately, the definition of catastrophic damage used was aligned with the conditions required to abandon the regular PSP measurements in the data set.

The modelling system used in this research derives forest productivity from a Site Index and a 300 Index, using the Site Index and 300 Index models. The Site index provides a measure of height and the 300 Index model produces the total volume. The combination of both determines average stem size and shape along with a taper equation. Site Index is defined as the Mean Top Height (MTH) at age 20 (Goulding 2005). The 300 Index defined as the mean annual increment for the volume of wood grown at age 30 for forest pruned to 6 metres and thinned to 300 stems per hectare final stocking (Kimberley, West et al. 2005). To calculate the 300 Index value the model relies on an algorithm to adjust for silviculture by taking into account any pruning or thinning history of the site and predicting the forest volume which would have been produced for that standard regime.

The expected values for Site Index and 300 Index are predicted from mapped productivity estimates for both Site Index and 300 Index as in Palmer, Hock et al. (2009). These New Zealand National radiata pine productivity maps predict the Site Index and 300 Index across New Zealand. They were created through regression modelling and spatial interpolation of measured Permanent Sample Plot (PSP) productivity indices from geo-referenced environmental variables. The maps can be used to look up productivity indices from location, and can therefore be used as a source of information for the simulation of forest growth on a given location without tree measurements. The error or difference between the predicted values in these maps and the productivity indices calculated from tree measurements is the productivity uncertainty which drives variance in the stochastically generated forest productivity simulations.

Variation from catastrophic damage was simulated by predicting the occurrence of wind damage and adjusting forest volumes and harvest costs to match observed damaged forests. The occurrence of wind damage is predicted from the difference between the resistive moment provided the tree root system using an equation based on stem volume from Moore and Quine (2000) and the calculated moment created by the wind on the tree canopy. To calibrate the difference in moments to probability of wind damage the difference between the two moments was adjusted to sum to the regional probability of wind throw as quantified by Moore, Manley et al. (2011).

By separating predicted productivity error into prediction error and catastrophic damage this study is able to isolate the contribution of catastrophic events and quantify the expected productivity reduction. Prediction error is presented for two silvicultural regimes with and without catastrophic damage. This research highlights the effects of volume prediction uncertainty on the financial appeal of forestry as an investment and gives guides on the likely reduction in value from catastrophic damage. Increased understanding of value prediction error and risk from catastrophic damage for forest investments will help to make New Zealand forestry a more attractive investment and provide options to handle uncertainty in forest value and carbon sequestration calculations.

Chapter 2 - Generating productivity indices

Objective

This chapter describes quantification of the distributions of Site Index and 300 index prediction errors and their correlation for the productivity maps across a case study forest. The prediction error was repeatedly sampled within a range of stand sizes to represent variance between forest stands. From the sampled errors a series of equations were calculated to stochastically generate productivity indices starting from mapped expected productivity, to be implemented in a stochastic forest growth model. The results enable productivity indices to be generated for stochastic forest growth simulations starting from expected values based on location alone.

Background

New Zealand National radiata pine productivity maps predict the Site Index and 300 Index productivity indices across New Zealand. Key geo-referenced input variables found in the regression of 300 Index are the Land Environments of New Zealand (LENZ) classes, summer degree frost days; annual water deficit and vegetation cover (1987). Key geo-referenced input variables found in the regression of Site Index are LENZ class, max temperature in summer, annual water deficit and vapour pressure deficit in autumn. The resulting maps can be used to look up forest productivity indices for a site from location coordinates, and can therefore be used as an alternative for tree measurement to estimate forest productivity. While the predicted index values represent the mean predicted index values for a site they do not describe the potential variance around that mean. This chapter will describe the mapped productivity prediction error in the case study forest so that productivity maps can be used as a starting basis for stochastic analysis. The expected productivity and errors will be stochastically generated to produce multiple productivity index combinations for repeated forest growth modelling.

Tree measurements of diameter and height within a known area can be used to calculate both 300 index and Site index for a sampled site where the silvicultural history is known. Calculations from tree measurements were independent of the forest productivity maps, as all plots used for regression of the maps were excluded from this data set. Tree measurement data was collected as Permanent Sample Plots (PSPs) as part of the Scion[2] national growth monitoring effort, and as a routine business practice for forest management companies tracking forest growth. In this study calculated values from selected PSPs were used to explore the variance in Site and 300 index values around the mapped productivity expected values. This data has been provided by Timberlands Limited (the forest management company) for Kaingaroa Forest in agreement with Timberlands that only the variance of these measurements will be presented and not overall productivity. This is in order to protect commercially sensitive forest growth information. Productivity index values are calculated for a large sample of locations within the forest to assess the prediction error of the models within Kaingaroa forest. The variation within forest stands for both smaller and large stand sizes will quantify the stochastic variation in the final simulations in this research.

[2] Scion is the trading name for the New Zealand Forest Research Institute (FRI) Limited, a New Zealand Crown Research Institute (CRI).

Method

The stochastic forest modelling system used to analyse forest productivity variation utilises repeated runs of the 300 Index growth model inside the Atlas Forecaster forest modelling software (Snook 2010). This system needs both a 300 Index and a Site Index value as inputs to calibrate the simulated growth rate for each generated run of the simulation. The following is the method by which the function was derived for stochastically generating Site Index and 300 Index pairs.

Selecting PSPs for productivity index calculation

A selection of plots from the PSP database for Kaingaroa was used to calculate 300 Index and Site Index values to compare with the mapped expected values. Suitable PSPs were those planted between 1979 and 1995, not abandoned as at 31st December 2000, with less than 50kg/h a fertiliser application, excluding nelder trials[3] and not used to make the 300 Index model or in the productivity map regression. The plant date constraint was designed to control for the effects of breeding and silvicultural management, as these have been refined to be more productive following the mid 1970's (Kimberley, West et al. 2005). The fertiliser limits and exclusion of nelder trials were done to keep silviculture of the measured plots inside the bounds of the 300 Index model silvicultural adjustment capabilities, and excluding previously used plots was to ensure the predicted productivity and verification data was independent.

PSP data for Kaingaroa Forest stored on the Scion PSP data base (Pilaar and Dunlop 1989) includes a combination of research plots in experimental trials and commercial growth monitoring

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[3] Nelder trials are planted in a circular arrangement with a set number of trees around each ring, but each ring with a different circumference. This results in a wide range of stockings on one site. The extreme range of stocking in these trials is outside the capability of the 300 Index silvicultural adjustment algorithm, and so they were removed from the data set

plots. This database contains a large number of plots for Kaingaroa forest covering a wide range of plant dates and silvicultural treatments. A data request was written for the PSP database system to produce 2476 measurements of tree diameter and associated selected heights across 483 plots appropriate for productivity index calculation. There were 2 distinct plot types; research trials where plots were planted close together with contrasting silvicultural treatments and growth plots where plots were spread out but had similar silvicultural treatments, as displayed by the plot symbols used in **Figure 2-1**.

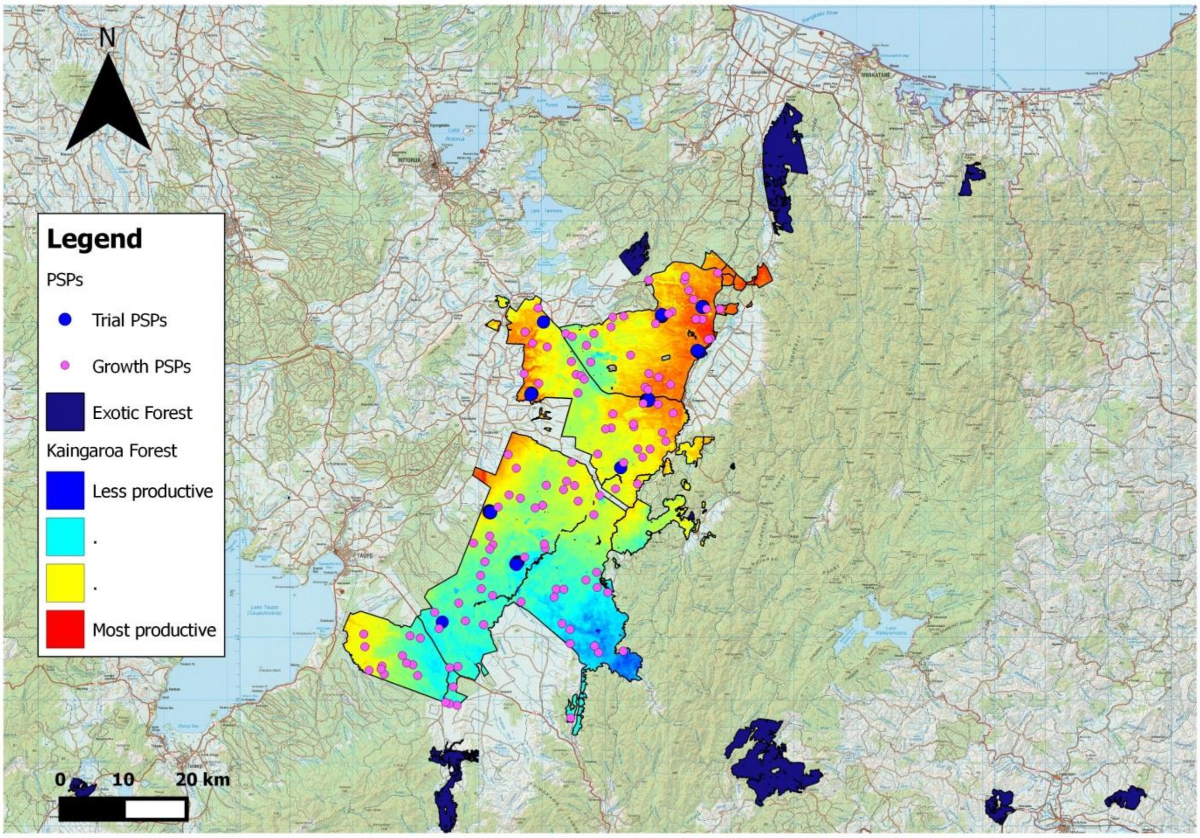

Figure 2-1: Location of growth plots and trials used to assess variation in Site Index and 300 Index in Kaingaroa Forest.

Calculating Productivity indices from PSP data

For each of the 483 plots a separate data file was extracted from the PSP database for measurements, thinnings, prunings, fertiliser applications, and the location coordinates for each plot. The data files were merged and sorted by plot identification and date for processing to be processed in the Forest Carbon Predictor (FCP) (Beets, Kimberley et al. 2011). Although it was designed specifically for carbon estimation, for the purpose of this study the FCP was used as a spreadsheet based implementation of the 300 Index model for productivity index calculation.

A requirement of the FCP is that there are no increases in stocking over the sequence of measurements for a plot, so the first process was to clean up stocking progressions over time for each plot. The stocking is measured as the number of tree diameter measurements per hectare, so causes of stocking increase include:

- An initial under-estimate of stocking, where the prescribed plant rate is exceeded by the planting contractor and this isn't picked up until the first plot measurement.
- Steep angled branches leaving the main stem below the 1.4m diameter measurement height and growing to compete with the main stem. This is particularly likely when the main stem is damaged by wind or other disturbance. Once branches are competing with the main stem they are treated as forks of the main stem and have their own diameters measured, increasing the stocking count.
- Toppled trees where they survive and multiple branches become vertical and grow to compete for dominance. These branches then compete with or replace the main stem and each diameter is measured, increasing the stocking count.

Where a stocking increase occurred immediately after establishment the initial stocking estimate was increased to match the first measurement. Where there was an isolated single measurement with an increased stocking it was assumed a measurement team incorrectly assessed branches as competing stems and the single stocking count was reduced to match the previous. One plot was removed from the data set because of a step up in stocking of 13 stems per hectare at 16 years of age.

The final step in preparing data for the FCP was ordering events so that measurement data was entered after silviculture where they occurred at the same age. Pruning or thinning events after the final measurement were removed from the data as they cannot be incorporated into calculations of the FCP without a follow up measurement to quantify the change in growth. The organised data set was run through the FCP. The results used from the FCP were the calculated Site index and 300 index for each plot, to be compared with the mapped values.

Referencing mapped estimates of productivity

Productivity map derived 300 Index and Site Index value with identification number and location coordinates were exported from the Scion PSP System and imported into the Quantum Geographic Information System (QGIS) (QGIS Development Team 2013). Also imported into QGIS was the productivity map shape files (Palmer, Hock et al. 2009) for 300 Index and Site index. There were a small number of plots with no location coordinates recorded. These plots were dropped from the data set as mapped productivity could not be extracted. This left 475 plots.

So that weightings by area were even across the forest at each trial where a large numbers of PSPs are on one site, only one representative plot was included in the dataset. As trials made up a significant portion of the dataset this step made for a significant drop in PSP numbers; the result was a total of 94 plots evenly spread across Kaingaroa Forest. For each plot the calculated productivity indices from the FCP and mapped modelled productivity indices, ready for comparison between calculated and mapped values.

Assessing mapped productivity error

With the productivity layers and plot locations virtual stand areas of contrasting areas were used to compare the mapped values to calculated values. Virtual stands from 1,000ha to 20,000ha were overlaid in a randomized grid onto the map to represent those stand sizes in error calculation. Inside each virtual stand all FCP calculated plot values and mapped plot productivity values were compared and the prediction error calculated. Where selection squares crossed forest boundaries the area was reduced to represent the area inside the forest only.

A nested analysis of variance was used to assess average productivity index error, error variance and error correlation between Site Index and 300 Index using SAS software (version 9.4) and the PROC MIXED function. Virtual stand area was used as a fixed effect for the intercept, and mapped plot productivity was nested within selection zone area and used as the random effects. The variance structure was set in PROC MIXED so that variance in Site Index was correlated with the variance in 300 Index. The resulting error variances and error correlation were used from SAS used with the bivariate normal function within each stand size to generate productivity index errors.

The bivariate normal function

Errors in the prediction of Site Index and 300 Index productivity indices have a strong correlation, meaning a site with over estimates volume growth (measured as higher than expected 300 Index) is most likely to have overestimated height growth (measured as higher than expected Site Index). For this reason the bivariate normal function was used. With this function each Site Index error was calculated from a corresponding 300 Index error given the mean error and standard deviation in errors and their correlation from the SAS outputs as per **Equation 2-1**.

Requirements for the bivariate normal distribution include normality of the variables and their errors and a linear relationship between the two variables. These assumptions were checked using the case study forest PSP data and calculated mapped productivity prediction errors.

Producing productivity pairs

To investigate different site types a pair of productivity indices were selected both for a high productivity and a low productivity and simulated at both the 1,000ha and 10,000ha stand size.

Errors for 300 Index were generated from a normal distribution with a mean 300 Index error from the SAS analysis and standard deviation as the square root of the variance between plots within each stand size. Errors for Site Index were then calculated from the 300 Index errors using the bivariate normal distribution and the Site Index error standard deviations and correlation from the SAS outputs for each given stand size. The errors were added to the selected high productivity and low productivity site values to produce productivity pairs representing the between plot variance.

Bivariate normal distribution function

$$\boldsymbol{E(S|V = v) = \mu_s + \rho_e \frac{\sigma_v}{\sigma_s} (V - \mu_v)} \qquad \textbf{(Equation 2-1)}$$

Where: S = The expected Site Index error;

V = The expected 300 Index error;

v = The actual 300 Index error;

μ_s = The average Site Index error;

ρ_e = The correlation between prediction errors in Site index and 300 Index;

σ_v = The 300 Index error standard deviation;

σ_s = The Site Index error standard deviation; and

μ_v = the average 300 Index error.

Results

Testing the normality of the Site Index and 300 Index errors between calculated productivities from tree measurements was done using plots of probability density overlaid by a normal distribution bell curve, as shown in **Figure 2-2**. Both the Site Index and 300 Index errors are normally distributed and have a small bias to be above zero indicating a small under-prediction by the productivity maps for the case study forest.

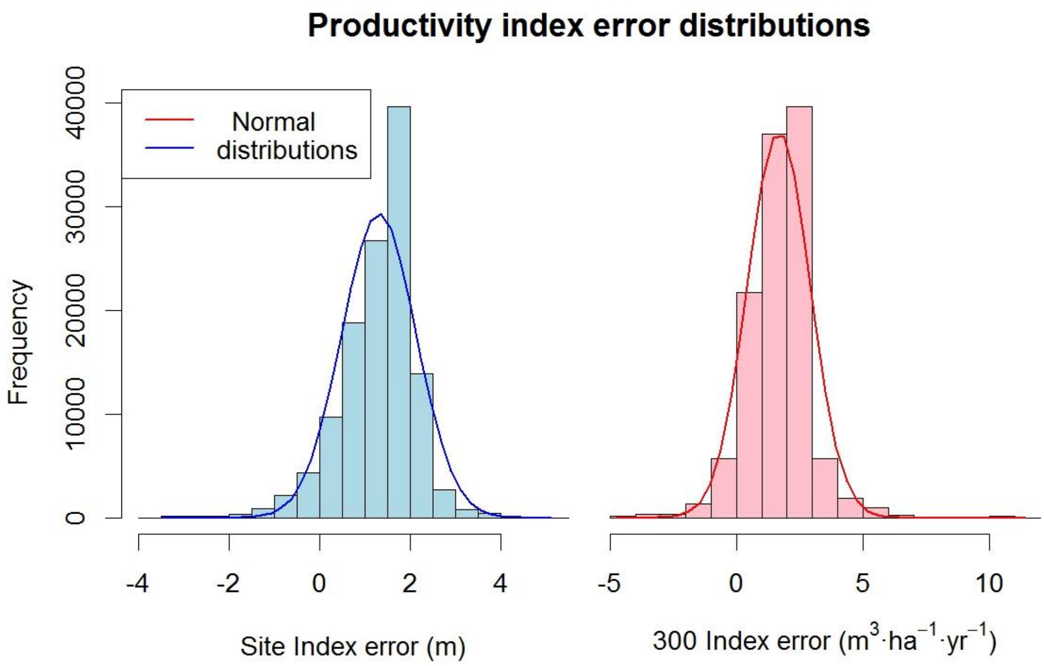

Figure 2-2: Test of normality for predicting Site Index and 300 Index errors.

A linear relationship between Site Index and 300 Index and between the respective errors is an assumption of the bivariate normal function. **Figure 2-3** shows that the linearity assumption holds true for both the productivity indices calculated from tree measurements and the errors in their mapped estimates.

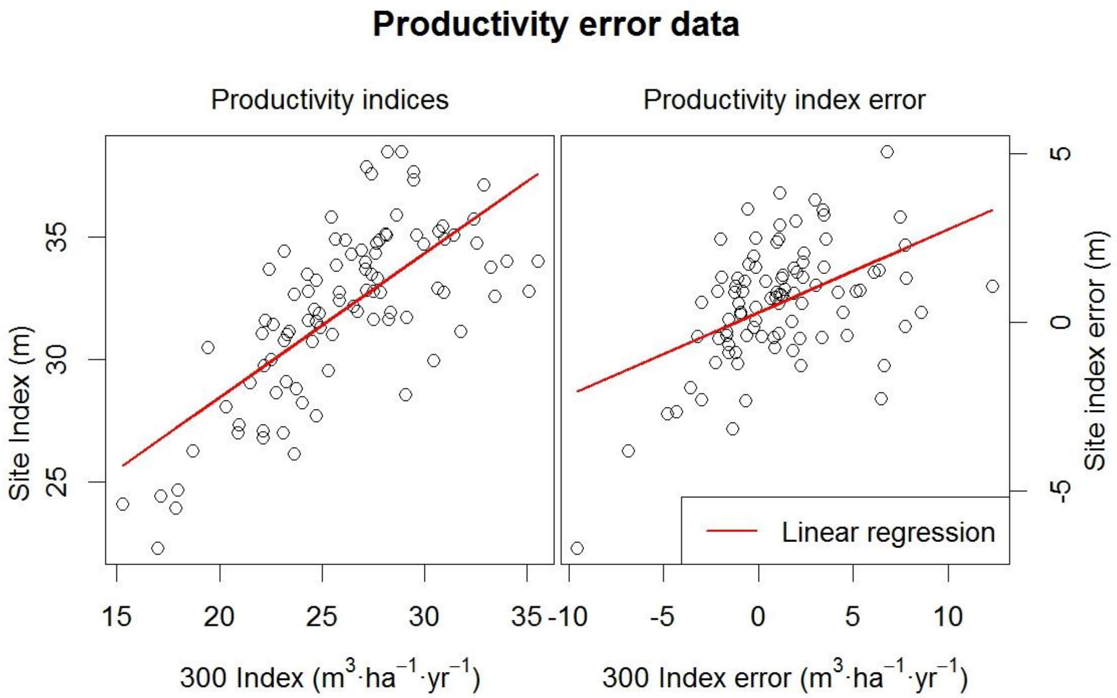

Figure 2-3: Plotted Site Index and 300 Index from tree measurements for PSP sites and the respective errors in mapped productivity estimates

Because PSPs are spread throughout Kaingaroa Forest it was not possible to get enough data points within selection zones lower than 1,000ha with meaningful results for mean error, or error standard deviation. Therefore 1,000ha is the smallest selection size possible with this data set. 1,000ha and 10,000ha sizes are used for evaluating uncertainty in carbon sequestration and forest value representing medium and large stand sizes.

The regional bias in predicted error Site Index averages at 0.49792 across the 5 selection square sizes analysed. For 300 Index prediction error averaged at 0.959. These mean error values were used in the bivariate normal function for generating productivity indices.

Although only 1,000ha and 10,000ha were used in simulations the trend was assessed over a wider range of stand areas up to 20,000ha. **Table 2-1** shows the SAS analysis outputs for the multilevel analysis of variance in productivity index error, showing error variance and correlation across varying stand area. Both Site index and 300 Index show the same trend with a weak negative relationship between variance and stand area, while the error correlation was constant at 1 across all areas.

Table 2-1: Nested mixed level analysis of variance results for errors in mapped productivity index estimates.

Area (ha)	300 Index variance ($m^3 \cdot ha^{-1} \cdot yr^{-1}$)	Site Index variance (m)	Error correlation
1,000	3.872	0.9323	1
2,000	3.8708	0.9545	1
5,000	1.397	0.793	1
10,000	1.7138	0.6941	1
20,000	1.8542	0.2219	1

Site Index variance was 0.9m for medium stands and 0.6m for large. 300 Index variance was $3.9m^3 \cdot ha^{-1} \cdot yr^{-1}$ for medium stands and $1.7\ m^3 \cdot ha^{-1} \cdot yr^{-1}$ for large. The square root of the variances was used in the bivariate normal function as it required the standard deviation in the formula. That is standard deviations of 0.97m and 0.83m for Site Index; $1.97m^3 \cdot ha^{-1} \cdot yr^{-1}$ and $1.31\ m^3 \cdot ha^{-1} \cdot yr^{-1}$ for 300 index for the 1,000ha and 10,000ha stand sizes respectively.

The 300 Index errors were stochastically generated from a normal distribution with the mean as the regional bias of 0.959 and standard deviations corresponding to the variances for each stand area. Using the means and standard deviations for each area and a correlation of 1 in the bivariate normal function (**equation 2-1)** the corresponding errors in Site Index prediction were calculated. The resulting error pairs are presented in **Figure 2-4**. There was a wider spread of values for the smaller area stand size as a result of the decrease in variance with increasing stand size.

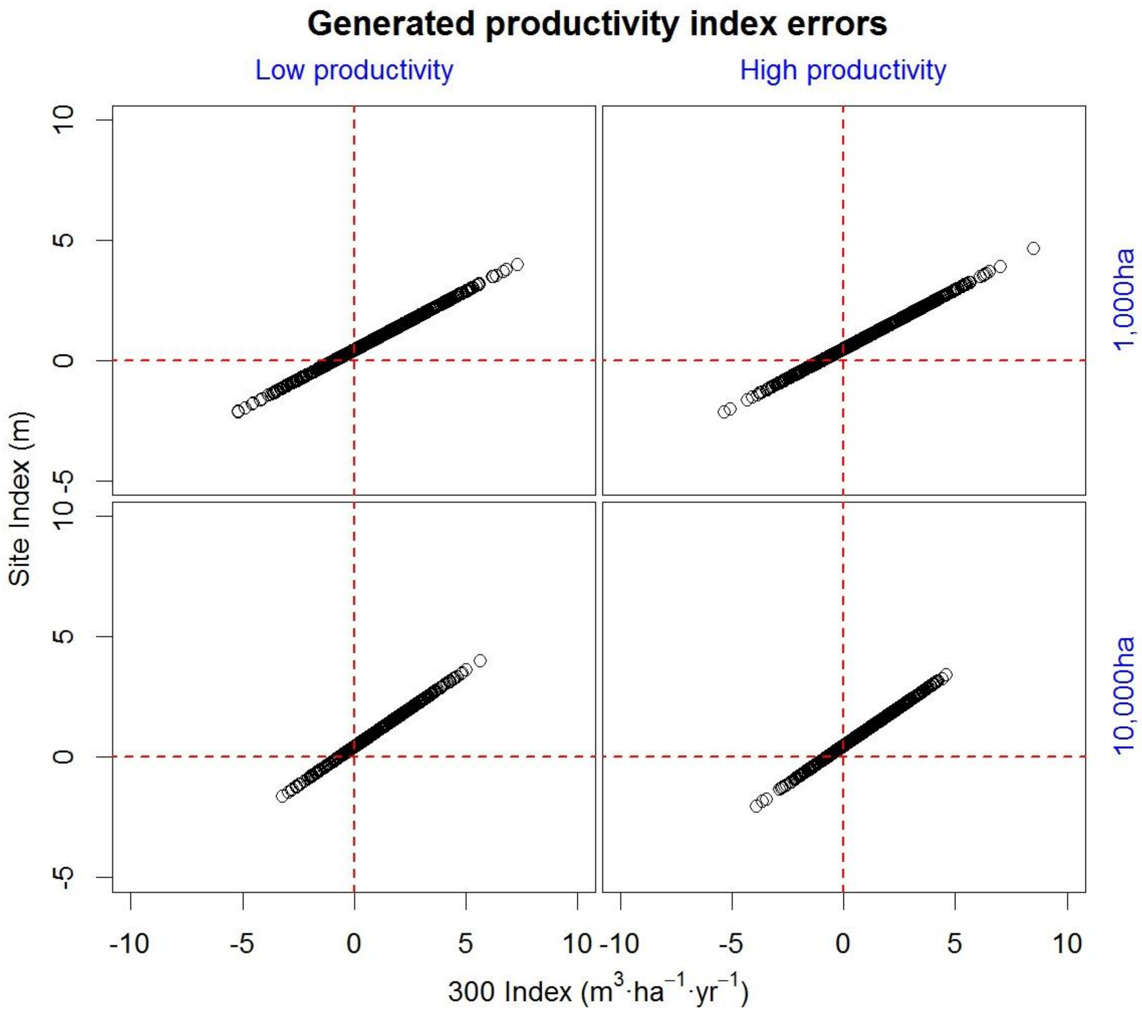

Figure 2-4: Generated Site Index and 300 Index errors for stochastic forest growth simulation

To produce usable productivity indices for stochastic forest growth simulation the generated errors were added to the low productivity and high productivity estimated values. These productivity indices are shown in **Figure 2-5**. The significance of the wider spread of values is less significant once the errors are added to the mapped estimates, reducing the effect of stand size.

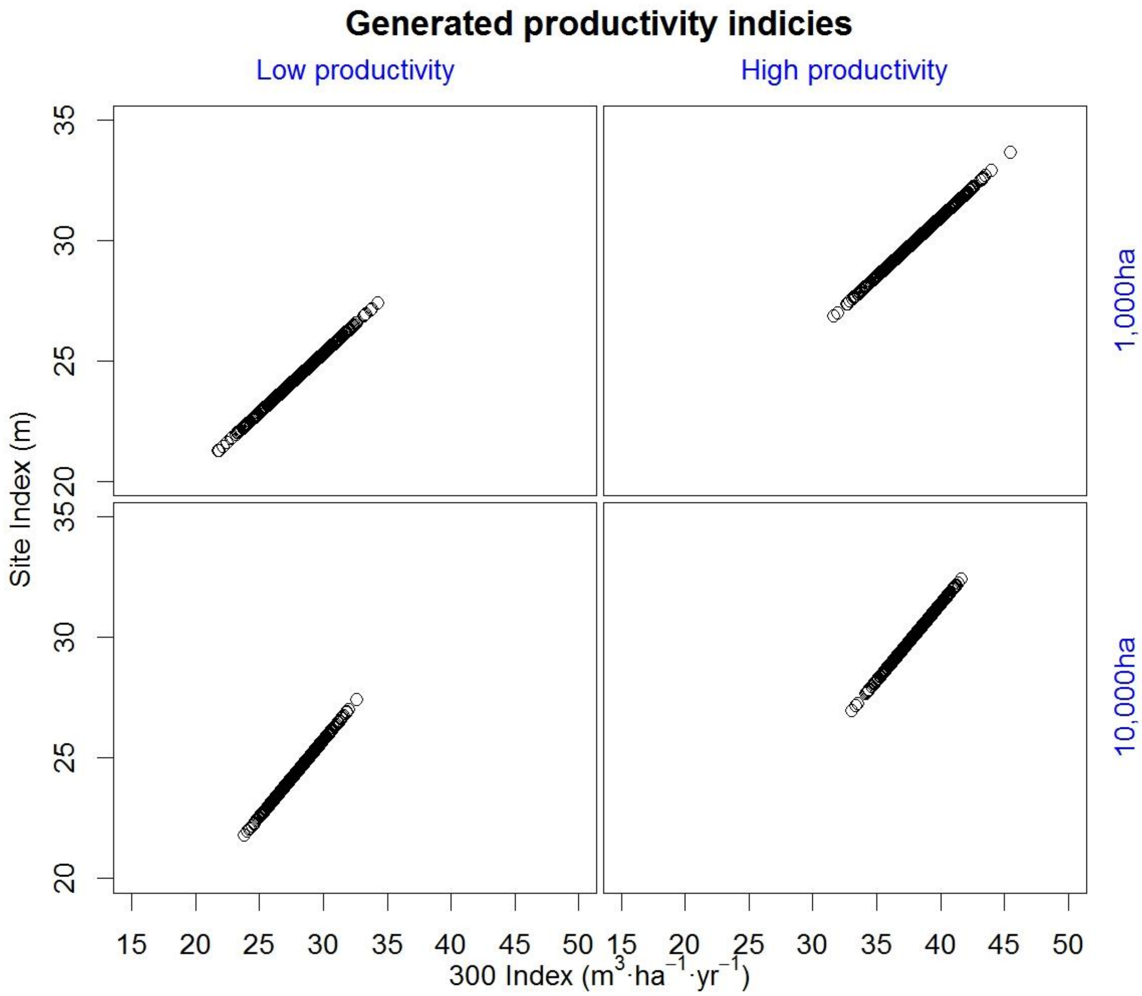

Figure 2-5: Generated Site Index and 300 Index values for stochastic forest growth simulation

Discussion

Generated productivity indices are used to simulate the uncertainty between forest stands. The uncertainty between stands is the focus because it underpins the likelihood of productivity outcomes for a proposed forest investment, as opposed to the option of another forest location.

The spread in error was wider for smaller forest sizes, shown by the weak linear relationship between area and variance in the nested analysis of variance and generated errors. The significance of the negative relationship was stronger for the errors than the overall productivity indices. Because of the weaker relationship for productivity indices it was unlikely that estimates of forest value and carbon sequestration from simulations and would have significantly more uncertainty for smaller forest investments.

The size for virtual stands sampled ranged from 1,000ha to 20,000ha. This range was the widest possible with the Kaingaroa dataset. Although Kaingaroa forest has a large number of PSP plots compared with other forests, this was still not enough to sample areas smaller than 1,000ha due to too small a number of plots inside each selection after unsuitable plots had been removed. Potential forest investors looking at forests smaller than this may face higher uncertainty than found by this study.

The two forest areas chosen for further analysis and simulation were 1,000ha and 10,000ha. These have been chosen to represent the smallest forest possible forest area with this dataset and a large forest investment for comparison. Only two contrasting areas have been chosen to limit the total number of combinations for simulations and final analysis once productivity, silviculture and catastrophic damage treatments are considered.

The 300 Index and Site Index productivity maps created by Watt et al. (2010) were modelled across New Zealand. Applying them over a case study forest found a small regional bias for both Site Index and 300 Index inside the case study forest. While the results will include realistic estimates of prediction uncertainty in carbon sequestration and forest value they will be specific to Kaingaroa Forest. The regional bias of the mapped productivity indices found in this analysis is minor at less than 5% and indicates the productivity maps to be a good starting point for forest modelling. From this starting point the process for generating productivity indices uses the Kaingaroa data to derive functions to predict the means and standard deviations for the indices.

Conclusions

The process for generating pairs of Site Index and 300 Index forest productivity values uses the nested analysis of variance outputs for standard deviations of Site Index and 300 Index errors, and the correlation between errors. The process of generating productivity indices for a site of a known size includes;

- looking up the expected mean values for productivity indices of a site using the mapped productivity surfaces from Watt et al. (2010),
- generating 300 index error values from a normal distribution with a mean equal to the mean error and a standard deviation from the nested analysis of variance,
- generating the matching Site Index error values from a the bivariate normal distribution function, using error standard deviation and correlations from the nested analysis of variance, and
- adding the errors to the expected values from the productivity index maps

The process will generate multiple pairs of productivity index values which will be used to generate input files for multiple Forecaster forest growth simulations. These simulations will be used to quantify variation in forest value and carbon sequestration. This in combination with the variable volume reduction from catastrophic damage will drive the variance in the stochastic forest growth simulations for the conclusions of this study.

Chapter 3 Catastrophic damage

Objective

Forest damage ranges from minor; for example where leaves are damaged by insect attack, the new growth at the top of the stem is blown off or branches are damaged; to major where trees are snapped or blown over and a large enough proportion of the forest is killed or severely damaged to financially justify abandoning the tree crop. For this research the effects of minor and major damage of forest volume are treated separately. Minor damage is captured as uncertainty around the expected forest growth and is described in the previous 'Generating productivity indices' chapter, while the major damage is investigated in this chapter. Specifically the purpose of this chapter is to assess catastrophic damage, so that in combination with the results of previous chapter both minor and major classifications of damage are included in the combined resulting stochastic simulation model.

Background

Wind damage is the most significant source of damage for New Zealand plantation forests, with on average 0.21 per cent of New Zealand plantation forest area abandoned due to wind annually based on records between 1945 and 2010 (Moore, Manley et al. 2011). In contrast only 0.024 per cent of forested area in New Zealand was abandoned annually due to fire in the period from 1991 to

2007[4]. Another source of potential forest damage is from biological causes, including fungal disease and insect attack. However, records of biological damage to New Zealand radiata pine predict a reduction in forest growth, rather than any area with damage severe enough to financially justify abandoning the crop (Chou 1991). As such biological sources of forest damage do not fit the definition used for catastrophic damage in this research and are therefore only indirectly included in the growth variation found in the 'Generating productivity indices' chapter. Rather than destroy the tree crop the most common impact of biological threats is an increase in forest management costs, due to the requirement for areal pest control spraying. Examples like the mountain pine beetle epidemic for *Pinus* species in the United States (Pappas 2013) and Canada (Alfaro, Campbell et al. 2009) are evidence that biological damage can be catastrophic. However, there are no records sufficient to estimate an annual area lost to biological sources in New Zealand, and so this effect cannot be included as catastrophic damage in stochastic simulation. Furthermore, it is assumed that any estimate of probability of catastrophic losses from biological sources would be significantly less than the area lost to fire, and less than the margin of error of estimation in this modelling system. For these reasons only wind and fire damage are analysed for the contribution to catastrophic forest damage in this chapter.

In September 2013 there were severe storms in the Canterbury region of the South Island of New Zealand, with 115km/hr recorded in Rangiora (NIWA 2007) and a large number of lightning strikes nearby. This resulted in catastrophic wind damage around the Canterbury region and a fire in Ashley Forest[5]. Prior to the Canterbury 2013 storms two Canterbury scientific radiata pine (*Pinus radiata*) genetics and silviculture trials and a two nitrogen growth plots had been measured in June

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[4] Percentage calculated from the average annual forest area lost to fire in Anderson et al. (2008) and the national forest area during that time in the NEFD (2014).

[5] Data on wind speed is from the NIWA Historic Weather Events Catalog. Online reference [accessed 5/01/2014] http://hwe.niwa.co.nz/event/September_2013_New_Zealand_Storm.

2013 as part of the Scion and Future Forests Research annual radiata pine measurement schedule, which aimed to collect data for long term forest growth monitoring. The two trials were affected by the wind damage and the nitrogen fertiliser growth plots were affected by fire.

The two wind damaged trials had originally been set up by the Stand Growth Modelling Cooperative (SGMC): The first of the two trials is FR 55 and was planted in 1988 (25 years old at the time of the storms), and the second is FR 121/12 planted in 1991 (22 years old at the time of the storms). These trials were selected for this study because they covered a wide range of genetic and silvicultural combinations and had been measured in the months immediately before the wind damage occurred. The forest management company Rayonier who managed the forest was contacted to confirm the level of damage at each site and for permission to access the damaged trial sites. Both trials had suffered significant damage. However, only FR 121/12 in Ashley Forest could be accessed for measurement due to salvage harvesting operations having already started in FR 55. The locations of these trials are shown in **Figure 3-1**. An aerial view of the damage to FR 121/12 after the wind storm is shown in **Figure 3-2**.

Originally 21 plots were planted in the FR 121/12 forest growth trial, which included five different genetic selection of radiata pine and 7 different silvicultural regimes. The combinations of genetics and silviculture planted at this site were intended to aid a nationwide growth modelling effort which was being undertaken at the time the trial was established. As such this trial does not include combinations of all genetic and silvicultural treatments, or any replications. The treatments in this trial were not designed to provide statistically significant results in isolation from the national trial series. When FR 121/12 was established a pruning treatment was intended. However, only the first pruning lift was ever completed. Because the natural green crown height at the time of the wind event had well and truly surpassed the low pruned height of pruned plots, for the purposes of this

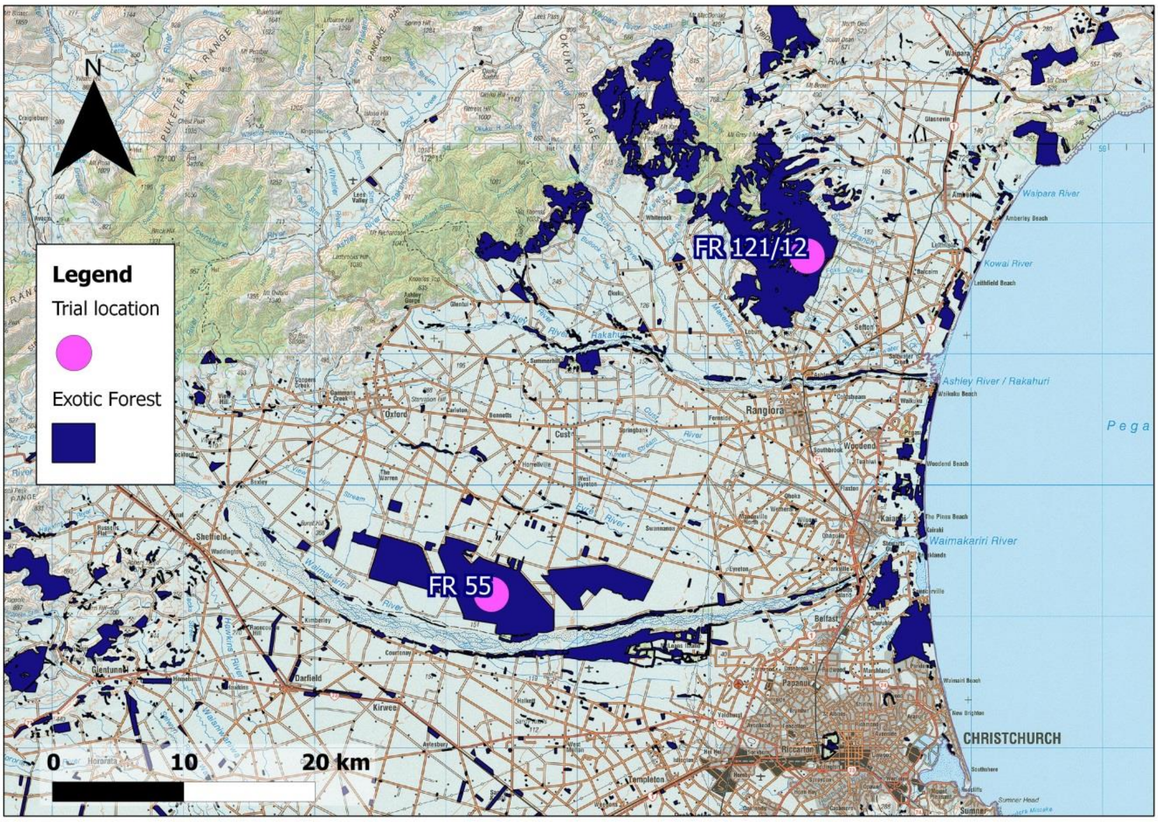


Figure 3-1: Location of recently measured trials damaged by the Canterbury wind storms.

Figure 3-2: Aerial view of FR 121/12 after the Canterbury September wind storms 2013 following the wind damage and showing the approximate location of each plot measured for this wind damage assessment.

assessment the pruned and unpruned treatments were treated as replicates. Due to differing past rates of tree survival the plots intended for pruning also provided additional stocking treatments filling in the range of stocking treatments for analysis. Despite the replication added by the incomplete pruning treatment the lack of intended replications in combination with the small area of the trial meant conclusions on the effects of stocking and genetics on the probability of wind throw was unlikely from the outset. Rather, this assessment was used to firm up assumptions used to stochastically model wind damage.

Accepted PSP measurement practice expects a minimum of 12 trees per plot to have heights and diameters recorded (Ellis and Hayes 1997), as opposed to the remainder of tree with diameter measurements only. This requirement ensures there is enough information to establish a Petterson curve relationship (Petterson, 1955) between diameter and height for each plot which enabled an estimated height to be calculated from diameter for all non-height trees. To ensure meaningful results unaffected by stem damage or abnormal growth trees selected for height measurement must have normal form, meaning no trees forked below breast height with excessive lean or broken or dead tops (Ellis and Hayes 1997). For this reason height trees were selected for wind damage assessment in FR 121/12, as they were known to be standing straight and have good form to provide an unbiased sample for wind damage assessment immediately prior to the September Canterbury storms.

The location of the fire in Ashley Forest was not far from the FR 121/12 experiment site. The two nitrogen fertiliser monitoring growth plots planted in June 2000 and were situated inside the fire affected area. The nitrogen growth plots were 13 years old at the fire. These plots had been set up to provide a comparison between fertilised and unfertilised plots as part of a national series of plots set up to monitor the tree growth response to fertiliser. At each site in the series one plot had received a nitrogen fertiliser treatment while the other was a control and was not fertilised. These two plots were assessed for the effects of fire on the volume of the stand following fire damage.

Method

The method for assessing catastrophic damage covers assessing the wind damaged trial and analysing possible causes of wind failure to form assumptions around the mechanics of tree failure under wind pressure, and designing appropriate wind damage stochastic simulation procedures. The process is repeated for the fire damaged plots but with less analysis due to the smaller number of plots in the burned area and more simple nature of forest fire damage in the specific case sampled.

Prioritising plots for wind assessment

Because of the difficulty of movement in wind damaged trials we prioritised plots for wind damage modelling prior to assessment. This enabled meaningful results without having to measure every plot in the trial in the time available. High priority plots were those with genetic growth and form ratings of:

- 'GF25 from the '268' series bred by controlled pollination,
- 'GF6' selected from the original radiata breeding population in New Zealand, and
- 'GF14' from the '850' series bred through open pollination

'GF25' and 'GF6' plots were chosen because they contrast each other with 'GF6' being an early genetic breed with seed collected from original New Zealand radiata pine, while 'GF25' represents a more refined genetic breed with known parents selected for growth and form. Furthermore, these genetics were planted in the trial over a wide range of stockings as opposed to other crop types which only covered a limited range

Trial measurement

Measurement of the FR 121/12 trial site occurred over 2 days in December 2013. Access to the trial site was difficult because of forest damage in neighbouring stands and high salvage logging activity in the area, which closed some forest roads. Due to the dangerous nature of wind damaged forests the measurement of the trial was undertaken in calm weather and in communication with the forest management company. The field measurements were undertaken with an experienced field technician from Scion who was involved with the trial from early on and is familiar with the trial layout and original setup to aid navigation with plot markers damaged and trees toppled.

Prior to the wind damage assessment tree diameter and height measurements from the June 2013 Permanent Sample Plot (PSP) measurement were transcribed into the Atlas Cruiser inventory software. Transcribing was done so that no diameter and height measurements were needed in the field and the work was as quick and efficient as possible. Once all measurements were transcribed an Atlas Cruiser Data Interchange (CDI) file was used to import data from Cruiser into the Atlas FieldMan data capture software. FieldMan was run on an Allegro CX field computer on which assessments on the shape, branch size and smashed sections of the trees were entered, as well as the tree status of; standing, toppled or snapped. The use of primary and secondary plots is a feature of Atlas Cruiser where the heights and features of the primary plots are used to characterise the combined crop type. For this field measurement primary plots consisted of the height trees, and the remaining trees in the plot made up the secondary plots. Height trees in the primary plots had, branch size classes, shape features and wind damage recorded, while the secondary plots did not require any assessment on the day and their data consisted of the previously transcribed diameters only. The number of height trees per plot measured in the June 2013 measurement of FR 121/12 varied between 11 and 20.

All stocking combinations with the selected genetics were measured, from below 100 stems/ha to over 750 stems/ha. In addition 2 'GF14' plots as well as one extra plot with a genetic growth and form rating of 'GF16' were measured. In total 14 plots were measured which included:

- 6 'GF6' plots at 122, 153, 343, 343, 600 and 780 stems/ha

- 5 ‘GF25’ plots at 92, 153, 271, 433 and 780 stems/ha
- 2 ‘GF14’ plots at 153 and 840 stems/ha, and
- 1 ‘GF16’ plot at 194 stems/ha

Quantifying wind damage

Following assessment of FR 121/12 the updated CDI file was imported back into Cruiser for analysis. Two separate harvest simulations were done; one with wind damage features included and one without. The first assessed volume from tree diameters, height, branch size classes and defect features for a no-wind damage scenario. The second included the addition of wind damage such as breakages and smashed sections which were programmed in Cruiser to be incompatible with all log grades, and represented the post wind damage log recovery of the trial for comparison. Recoverable log volume and value were calculated, with values based on long term MAF indicative New Zealand log specifications as shown in **Table 3-1**.

Analyses focused on the numbers of toppled, snapped and standing trees; comparing standing and non-standing trees using generalised linear regression to predict the logarithm of standing or not-standing as a binary result. The second set of analyses used the difference in value between assessments with and without wind damage included to assess losses in the September winds across the range of stocking and genetic growth and form ratings.

Table 3-1 Log grades to be used for log bucking in Atlas Cruiser software for wind damage assessment[6].

Log Grade	Log status	Small end Diameter (mm)	Maximum Knot (mm)	Sweep (% dia/m)
Large pruned	Pruned	400+	0	5.9
Medium pruned	Pruned	300-399	0	5.9
Large unpruned, small branches	Unpruned	400+	60	5.9
Medium unpruned, small branches	Unpruned	300-399	60	5.9
Small, small branches	Pruned or unpruned	200-299	60	5.9
Large, large branches	Unpruned	400+	140	5.9
Medium, large branches	Unpruned	300-399	140	5.9
Small, large branches	Unpruned	200-299	140	5.9
Pulp	Unpruned	100	n/a	47

Results

The analysis looks into trend in forest damage and the change in merchantable log grades for the both the wind and fire damaged PSPs.

Wind

Significant wind damage was evident at the FR 121/12 silviculture experimental trial in Ashley Forest with a large portion completely flattened. Toppling was the most common method of failing, as opposed to trees snapping. Often toppling did not result in breakage along the stem and trees were lying in tact on the ground down to a 10cm diameter, in which case no simulated change in log grades resulted.

[6] Prices used were based on specifications and long term prices from the Ministry for Primary Industries at Ministry for Primary Industries Log Grade Specifications, Online Reference. [Accessed 29/10/2012] http://www.mpi.govt.nz/news-resources/statistics-forecasting/forestry/log-grade-specification.aspx.

Figure 3-3 shows a view of the South-Western end of the trial with most trees lying flat. Only a small number of snapped and standing trees can be seen in the background. **Figure 3-4** shows an example of a typical toppled tree in the trial with the root plate lifted and stem on the ground.

The effects of wind on the site were not uniform across plots. Damage ranged from 100% toppling to no damage at all. There was a general pattern of wind damage and tree direction following the topography indicating a wind path across the trial from West to East, as can be seen in **Figure 3-2**. The largest area of continuous wind damage started at the lowest stocked plots which were thinned to a residual stocking of 100 stems per hectare. The damage and carried on up the hill from these plots in the direction of the wind into other higher stocked treatments.

Figure 3-3: Outlook over the South-Western end of the trial

Figure 3-4: Typical wind damage in the FR 121/12 trial; a toppled tree with exposed root plate.

The number of stems measured in each plot and their status of snapped, toppled or standing is shown in **Figure 3-5**. It shows that the most common method of failure was toppling, where the root plate of the tree has lifted. Stems were classified as snapped where the tree had suffered catastrophic damage during the storm and the bottom section of the tree was still standing upright. Plots which stand out in **Figure 3-5** are;

- plot 9/12 with all measured stems toppled,
- plot 12/13 with all measured stems standing, and
- plot 7/14 with over a third of all measured trees snapped.

There was a general trend for less damage of higher rated GF factor crop types, as is shown **Figure 3-6**. There was no trend evident for this data set for the effect of stocking. **Table 3- 2** displays the mean and 90% confidence intervals for probability of windthrow during the wind event for each crop

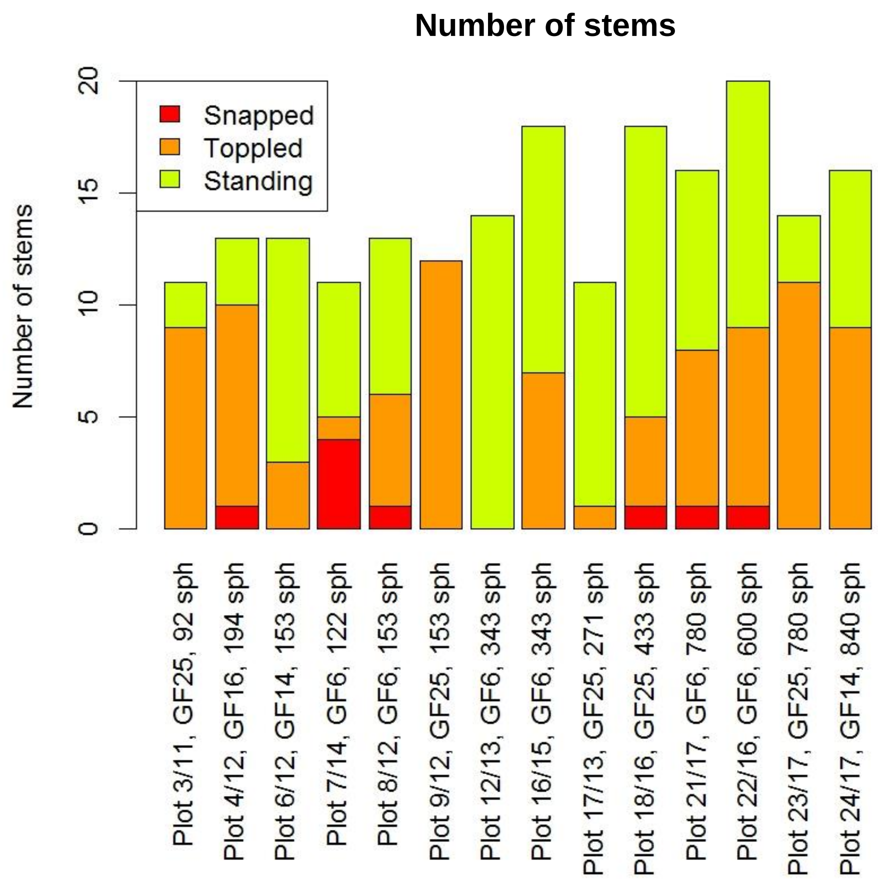


Figure 3-1: Number of stems by status for plots in the FR 121/12 forest experiment following the Canterbury September 2013 wind storms

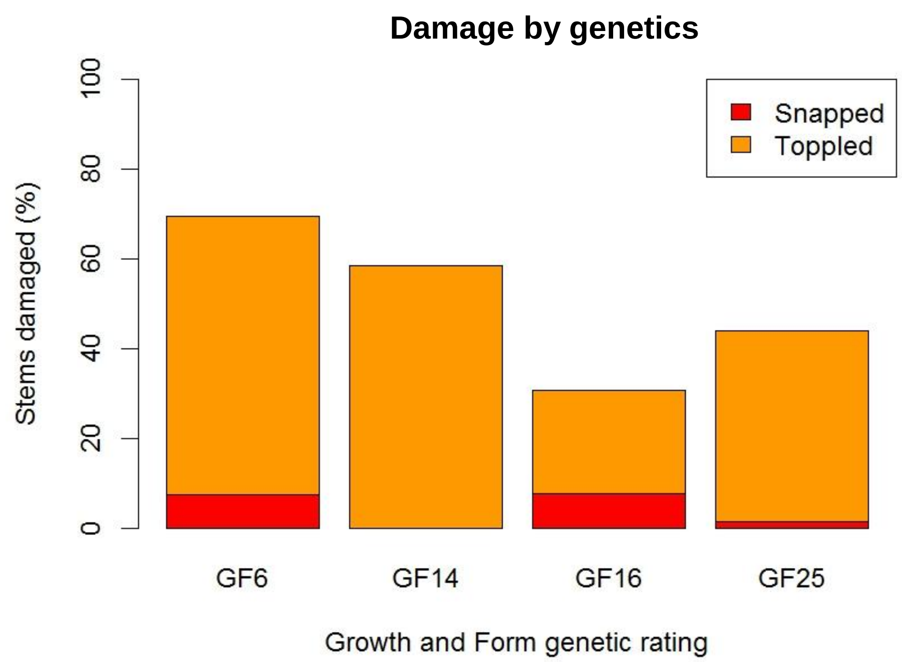


Figure 3-2: Percentage of measured trees which failed by method of failure in the FR 211/12 experimental growth trial in Ashley forest following the September 2013 wind storms.

type at 400 stems per hectare. From **Table 3- 2** it shows that GF16 and GF25 crop types had a statistically significant lower probability of wind throw than the GF6 climb and select crop type. The GF 14 and GF16 crop type was not well represented over the trial due to the trial design. With only two plots for GF14 and one for GF16 measured the significance of the results may be a false positive or type 2 error.

Table 3-1: Probability of wind failure in the FR 121/12 trial in the Canterbury September 2013 wind storms for different genetic growth and form ratings at 400 stems/ha

	Probability of windthrow at 400 stems/ha		
	Mean	Confidence Intervals	
		5%	95%
GF6	0.62	0.54	0.70
GF14	0.61	0.45	0.75
GF16	0.21	0.08	0.44
GF25	0.42	0.32	0.52

Figure 3-7 shows the volume change by log grade for each plot. In showing volume change by grade this graph displays how volume was re-allocated to different log grades following wind damage. Bars below the zero line show log grades which lost volume while bars above the zero line show log grades which gained. The most obvious trend is for an increase in the amount of waste at the expense of valueable grades. Waste increases when wood can not be allocated to any other log grade due to the log not being within grade specifications for small end diameter, branch knott size or log straighness as per the specifications shown in **Table 3-1**. It was also common for pulp to gain volume because of its more lenient specifications. 6 plots had no change in volume despite 5 of those plots having some trees topple in the wind event. This is because toppled trees with no smashed sections below 100mm diameter resulted in no change in log grades. Of note plot 9/12 identified earlier for having 100% toppling resulted in no change in log value. Also of note is plot

7/14 where as would have been expected with the high rate of snapped stems there was a large volume change. This volume change was second only to plot 21/17. This indicates plot 21/17 had a high rate of smashed stems during the windstorm even though toppling was the most common type of tree failure.

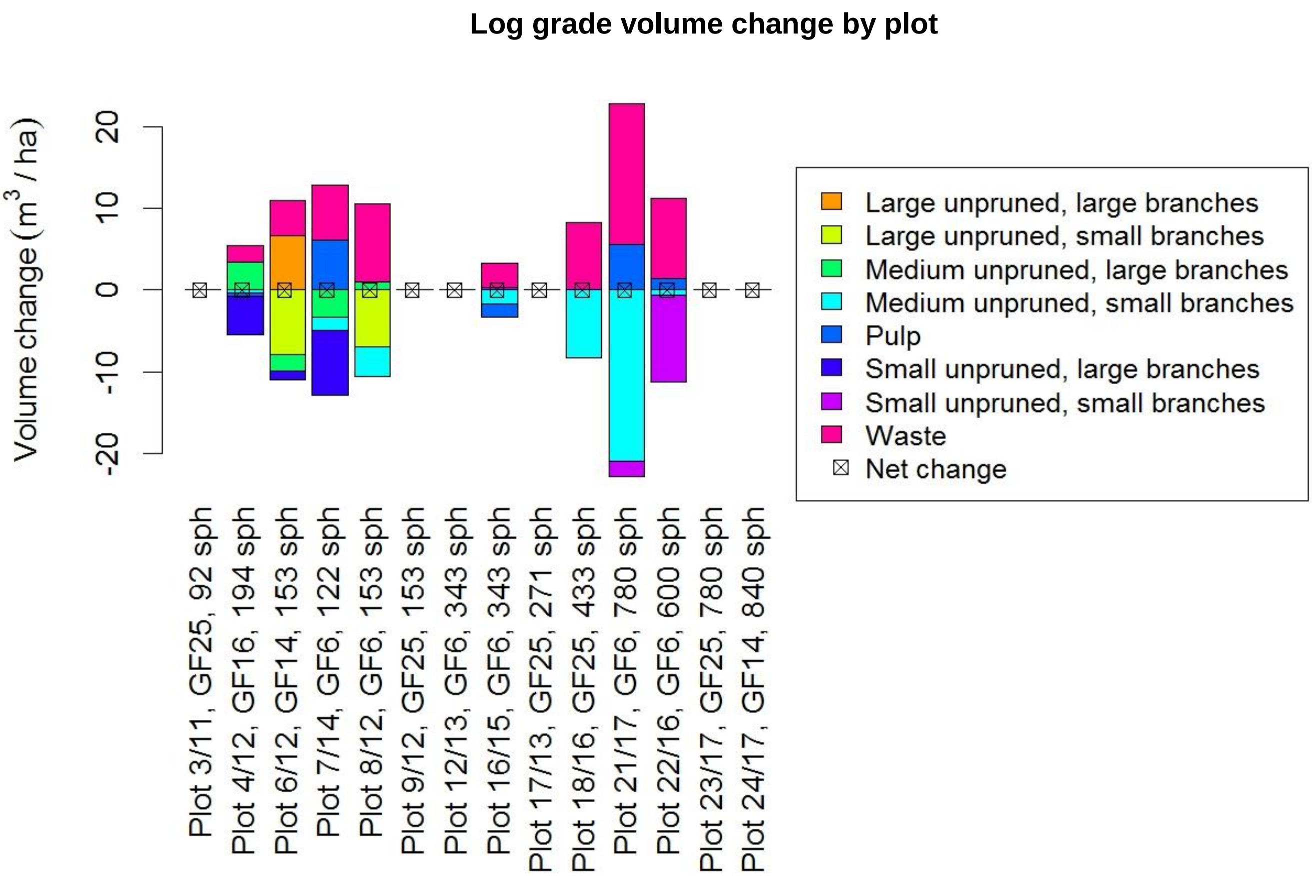


Figure 3-3: Volume change by log grade following damage in the Canterbury September 2013 wind storms for each plot in the FR 121/12 trial in Ashley Forest.

The overall value change for a plot is driven by the change in log grade volumes. **Figure 3-7** shows the change in log volumes, while **Figure 3-8**Figure 3-7 shows plot value change in dollars per hectare resulting from that volume difference. The overall net value change in **Figure 3-8** for each plot is represented by the crossed square symbols. There is a wide range of value changes from no change to a loss of $1950/ha. The large loss occurred in plot 21/17. The net change is made up by a drop in value of $2287/ha from losing 21 m^3/ha of the “Medium unpruned, small branches” log grade and 1.8 m^3/ha of the “Small unpruned, small branches” log grade. Which was slightly offset by a gain of $338 from an additional 5.6m^3/ha of the “Pulp” grade. All but one plot had the reduction in value partially offset by an increase in other grades due to the optimisation done in the simulated bucking. For example in plot ‘4/12’ there was a decrease of 4.8 m^3/ha in the ‘Small unpruned, large branches’ grade, but this was largely ofset by an increase of 3.4 m^3/ha in the ‘Medium unpruned, large branches’ grade.

Comparing the mean difference in value lost between GF6 and GF25 plots with a t-test resulted in a p-value of 0.07642, meaning we cannot reject the possibility that the means are equal at the 95% confidence level. The mean decrease in value from wind damage in the Canterbury September 2013 wind storm for GF6 plots was $833 with a standard deviation of $693. The mean decrease for GF25 plots was $165 with a standard deviation of $369. There were not enough GF14 or GF16 trees measured to justify a comparson of means.

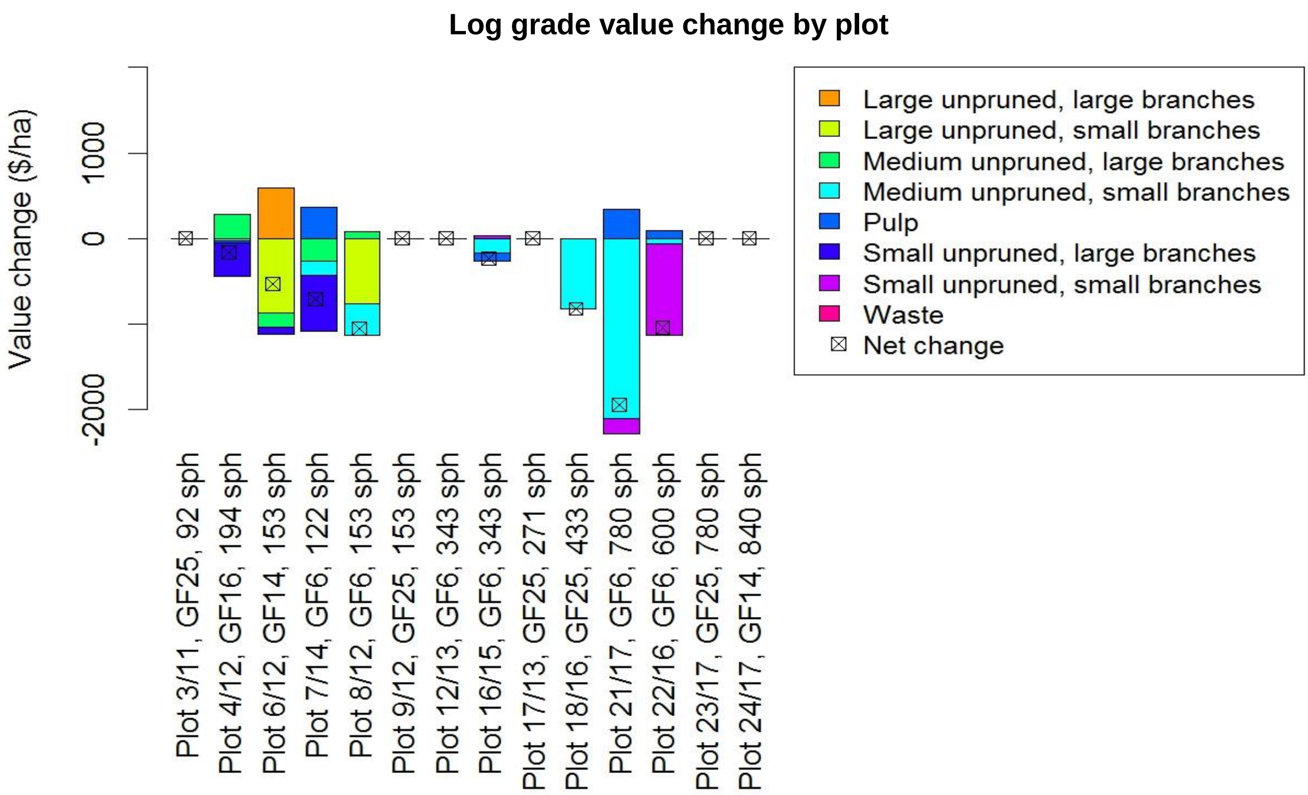


Figure 3-4: Value change by log grade following damage in the Canterbury September 2013 wind storms for each plot in the FR 121/12 trial in Ashley Forest

Figure 3-5 shows the average change by log grade across all plots in the trial, covering all silvicultural treatments. The change for most grades averaged out to around zero, except for the waste grade which was at 33% higher after wind damage. Because of the limited sample size the 95% confidence intervals for all log grades were large and included zero. So while the results on the increase in the waste grade are not conclusive, they will be used to guide assumptions made for stochastic simulations.

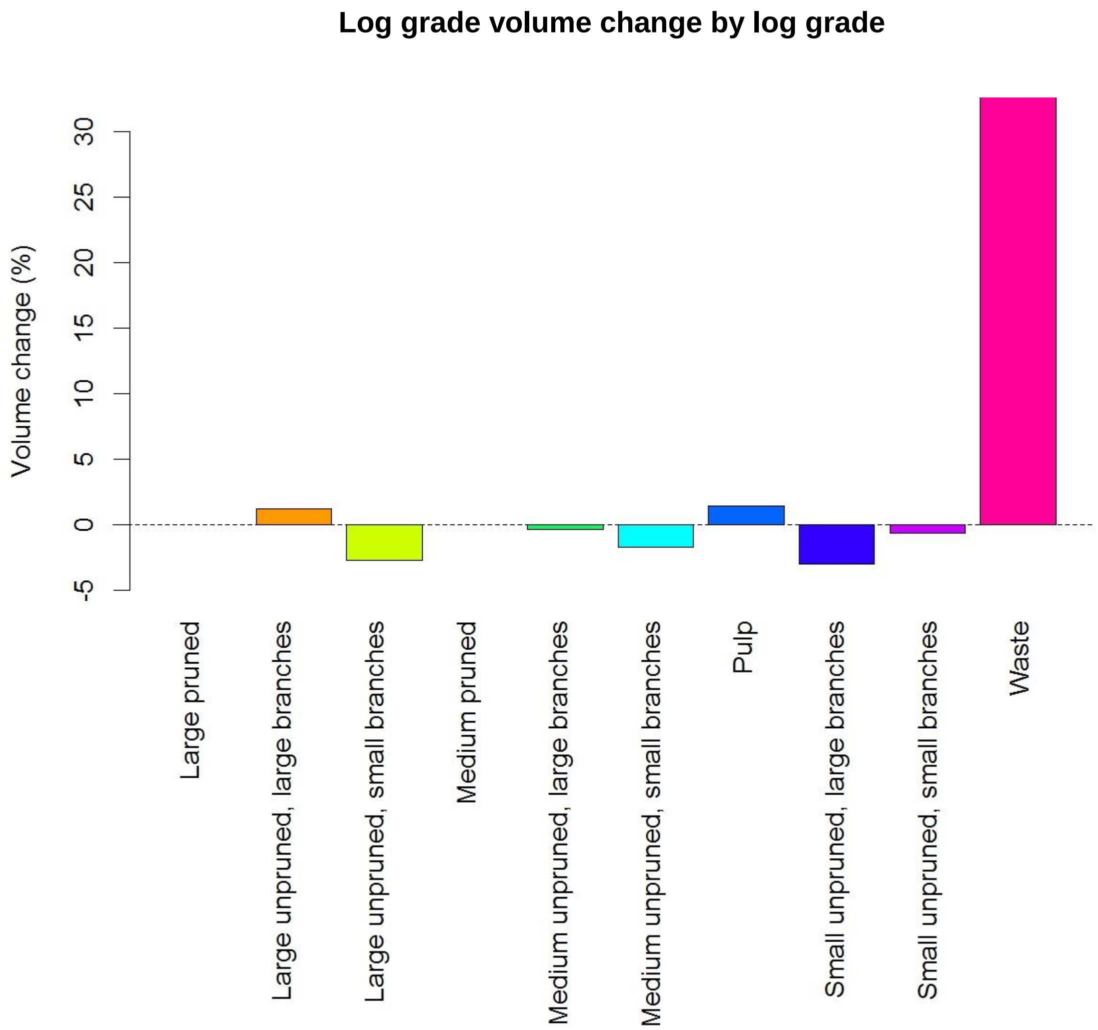


Figure 3-5 Average percentage change in log grades across all silvicultural treatments in the FR 121/12 experimental trial in Ashley forest

Fire

The assessment of nitrogen fertiliser growth plots found no change in diameter or height above what is normal for recently dead or severely unhealthy trees during re-measurement. Therefore, the fire resulted in no change in log grades. However, there was significant browning of the crown at the time of measurement. The crop was not expected to survive, and so due to the young age the timber value of this crop was zero.

Discussion

From the analysis on in Ashley forest following damage from the September 2013 storms in Canterbury this study looks at the determinant factors for the probability wind damage to occur in a stand, and following wind damage how the value of logs from that tree crop is affected. The effect of fire on log value is also discussed.

Probability of wind damage

From observation of the aerial photo of the trial following the wind damage, as well as evidence from previous research (Somerville, Wakelin et al. 1989, Moore and Somerville 1998, Moore, Manley et al. 2011) a major determinant of where wind throw occurs is the proximity to a stand edge, or somewhere the wind has an opportunity to catch the tree canopy and start wind damage. This occurred in the Ashley forest trial where the largest area of continuous wind damage followed downwind from plots with low stockings, where wind could penetrate the canopy. In contrast to experimental trials the silviculture employed in production forests is uniform and continuous. Therefore, the average distance between trees is a useful factor in simulations for determining how the wind will catch the forest canopy. Due to this effect and the nature of Forecaster simulations tree stocking can be conveniently employed from Forecaster outputs to predict wind damage susceptibility.

As well as winds' ability to catch the tree canopy, the ability of the tree and its' root system to resist the force of the wind is also a factor in determining the probability of wind damage. Tree volume is a good indication of the maximum resistive force which can be applied by the root system (Moore and Quinne 2000). Exceptions to this rule will be where root development is limited, and the potential resistive force of the roots is not reached, in which case toppling rather than snapping becomes more likely. Limiting soil conditions for root depth can be caused by a high water table limiting the depth of the root system or a hard impenetrable soil layer or rock pan. In the Ashley FR 121/12 trial toppling was by far the most common form of tree failure. There was some evidence of a high water table at the northern end of the trial where tree failure was most severe, with water pooling in the depression left by the roots despite the dry weather during and leading up to the period in which the trial was assessed. A high water table may be the reason for shallow root depth and therefore a high incidence of toppling.

The case study simulation is based on Kaingaroa forest, where there are known areas with a shallow hard soil pan which limits root depth if not broken up before trees are planted. However, site preparation techniques are used in Kaingaroa to break the pan with a specially developed excavator attachment, which has been shown to positively affect tree growth[7]. Accounting for root depth in the simulations for this research would require a function for resistive forces given the potential root depth and a map of potential root depth across the Kaingaroa case study forest. Neither of these is available. It is assumed that due to the systematic site preparation techniques employed in the forest the effect of the pan on root depth can be ignored for the purpose of this research.

The genetic effect on tree failure evident in the results was not significant across all rates of tree stockings, but was significant around 400 stems per hectare; the stocking around which most plots were at during the time of the storm and hence a larger sample size to achieve statistical significance. The genetic effect may be driven by the form characteristics, as the higher GF factor will have been selected for improved form, as well as growth. The genetic component to the probability of tree failure found in the FR 121/12 Ashley Forest trial did not transfer to a significant correlation between genetic group and value change. Despite tree volume not being significant in this analysis

[7] Presentation by David Balfour at the 2014 annual 'Timberlands contractors' health and safety meeting'. 12th December 2014.

for probability of failure, higher GF trees will have a faster growth rate and therefore also a larger root plate, which will increase the maximum resistive bending moment provided by the root systems. An explanation for why the relationship with volume was not significant may be the effect of shallow root depth in combination with wind catching the canopy of low stocked to start strips of wind damage, confounding the expected underlying relationship.

From previous research and the observations made during the assessment of the FR 121/12 trial following wind damage it is believed higher probability of wind damage is driven by volume growth and space between trees. With exceptions being when the root growth is limited by soil conditions and the tree canopy is not uniform. Volume growth and space between trees can be used to create an index useful for comparing the likelihood of wind damage between stands, but cannot define the overall total probability of wind damage. To achieve a prediction of wind damage probability the sum of the index must be matched to a pre-defined average rate of loss per year per hectare. The pre-defined rate should be referenced to real data from wind damage surveys.

The measurement and analysis of results from this trial is intended to give an indication to possible trends with genetics and stocking and the probability of wind throw and aid understanding in the mechanistic process of toppling trees under high wind turbulence. This information acted as a guide for parameters used in the Forecaster growth modelling software when simulating catastrophic wind events.

Change in log grades

The value loss from wind is a function of the reduced opportunities for log bucking, as the damaged sections must be excluded from the merchantable logs. The result is a reduction in volume of more valuable log grades, which is partially offset with an increase in the volume of lower value log grades and further loss from volume which must be cut to waste. Therefore, the overall value loss is dependent on the degree to which trees are damaged along the stem and the price differential between high value and low value log grades. There are two situations in which the loss from wind damage for a given wind event is limited:

- Where wind and soil conditions in the area mean that trees are blown in a similar direction and roots are shallow so that trees will topple rather than snap, so there is less stem damage to limit log bucking options.
- Where the log market provides a small difference in price between high value and low value logs, so that the value loss due to volume transferred into lower value grades result in less of a change in value.

By using the Forecaster simulation with current log prices this research will incorporate the effects of wind damage on log bucking by simulating the harvest early, at the time of wind damage, and by reducing the number of high value logs to a total of 33% of the waste grade. The effect of this on the resulting log grades in combination with a higher assumed price for salvage harvesting will represent the negative financial effects of wind damage in simulations.

Fire damage

No change in tree size or shape was evident from the assessment of the fire damaged plots in Ashley Forest. Furthermore, for this specific case the value of the tree crop following the fire was zero, because of the young age.

With no change in tree size or shape the change in forest value from fire damage is directly related to the timing of the event causing an early harvest. From this assessment no further analysis is required for fire damage. If trees at the time of a fire are large enough to produce merchantable logs, these will be valued as normal in simulation. This is based in the provision trees will be harvested before sap stain or other fungal or insect damage affects the timber (Knapp 1912). Due to this finding only wind damage requires further analysis to quantify the change in log grades following salvage harvesting.

The main contributors to catastrophic damage are wind and fire. While there is a description of the fire damage included in this chapter, the focus is on the effects of wind due to the more complex effect on merchantable log grades. The results of this chapter give a better understanding of the mechanics and effects of wind and fire damage on a forest in order to best replicate the effects of catastrophic damage in the stochastic value and volume production simulations, and describe the assumptions used to simulate fire damage.

Application in stochastic growth models

The stochastic growth model built for this research generated a large number of forest growth simulations which were run in the Atlas Forecaster forest growth simulator. The model applied wind and fire damage to a selection of forest growth simulations using a binomial probability selection based on the size and shape of the tree stem and tree crown for wind, and a simple random allocation for fire. Stands selected for wind throw were re-run with an early harvest simulated at the time of the assigned wind damage. The parameters used in the harvest simulation are set to replicate a true wind damage event based on the findings in this chapter. In the model stands selected for wind damage will include higher harvest costs and adjustment to the log grade output. Stands selected for fire will have an early harvest simulated at the time of the fire and will require no adjustment to log grades.

Conclusions

The relationship between the height and size of the sail area and the resistive bending moment provided by the roots drives the probability of wind damage. The probability of a stand suffering wind damage in a given year can be calculated by comparing the mean maximum resistive bending moment of the trees with a maximum likely bending moment applied by wind on the average tree crown sail area. The difference between the two must be and adjusted with a coefficient to match the surveyed average regional rate of loss per year (Moore, Manley et al. 2011).

From these results it is not possible to predict the proportion of snapped and toppled stems. However, the net volume change from wind damage can be predicted by increasing the log volume cut to waste. For this study the simulated effect on forest value was the loss in harvest value from being forced to harvest early, the change in log grades and the increased cost of salvage harvesting. The waste grade was increased by 33% at the expense of other more valuable grades. The decrease in other grades was spread evenly across the predicted merchantable logs for the given simulation.

Chapter 4 - Stochastic simulation

Objective

This chapter will describe the construction of the stochastic forest growth model, pulling together findings from previous chapters. It will cover how generated productivity indices are used, how catastrophic damage is simulated and how the functions are incorporated to stochastically generate multiple forest simulations using a statistics package and forest growth simulation software. The assumptions required to implement findings from previous chapters are outlined, including some additional regression on the Kaingaroa case study forest data and the implementation of formula for underlying physical relationships for catastrophic forest damage from wind and fire.

The results show how prediction error in forest growth productivity indices across a range of stand sizes and site productivities translate into uncertainty in carbon sequestration and forest value. Information is presented to provide confidence in carbon sequestration estimates and forest returns at the forest stand level for forest investors and for the New Zealand national carbon reporting effort.

Introduction

To date stochastic forest modelling has been used in forest research to test valuation and silvicultural practice, and compare optimal procedures under both stochastic and deterministic methods. Common uses of stochastic models in New Zealand forest research include predicting the optimum rotation length for stands, assessing potential wood supply across a forest estate and testing estate level wood supply scenarios, as described in Liley (2000), Manley and Wakelin (1989), and Brown (1996) respectivly. As computer processing power has increased so too has the complexity of these stochastic models (Liley 2000). This research continues that trend and has built a complex model where each simulation of forest growth is parametrised and set up in statistics software and run in forest growth modelling software. Final results are brought back into the statistics software for presentation of the distribution of NPV and carbon sequestration. By combining the two the software packages this system utilises the strengths and flexibility of both.

Method

This method covers how the stochastic model was constructed and run to simulate carbon sequestration and discounted forest value. The stochastic simulation model constructed for this research uses R statistics software (R Core Team, 2012) and Atlas Forecaster forest growth modelling software (Snook, 2010). The functionality in the R statistics language for generating distributions and processing information is extensive. The modelling system was semi-automated. The R statistics software communicated with Atlas Forecaster through Comma Separated Value (CSV) files specially arranged to fit the Forecaster format. These files were imported into Forecaster and executed using Microsoft Windows batch files via the Forecaster command line function. The process is summarised visually in **Figure 4-1** and explained further under the following headings.

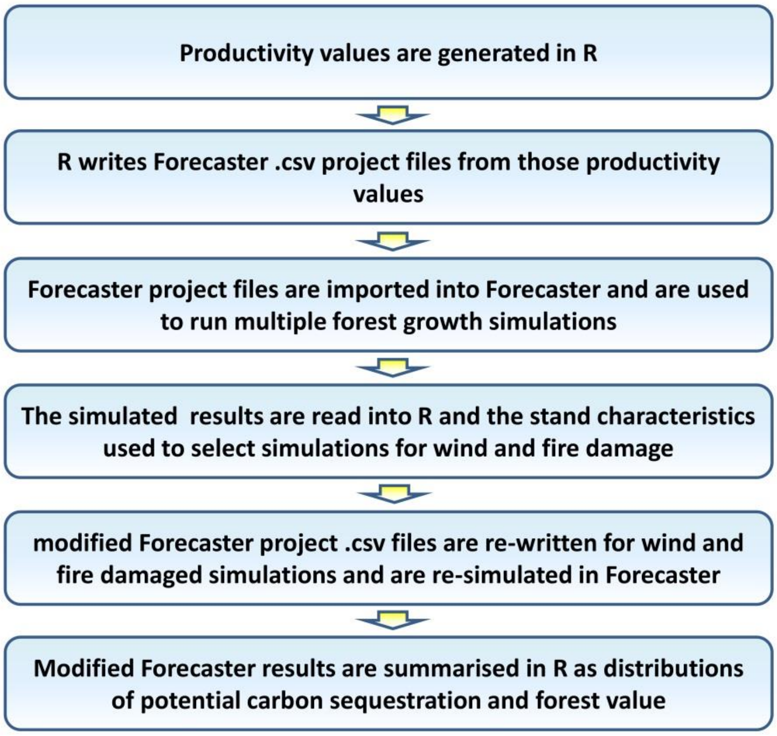


Figure 4-1: Process used in the stochastic forest growth and catastrophic damage model.

Generating productivity indices

The two productivity indices; Site Index and 300 Index are highly correlated. The relationship is covered in detail by chapter 1 - "Generating productivity indices". To generate productivity index pairs for simulation the functions derived in that chapter were written directly into the R code for the stochastic model. The 300 Index error was produced from a normal distribution with the mean equal to the mean error between the mapped and FCP calculated productivity estimates and standard deviation from the nested analysis of variance. The correlated Site Index errors were calculated from the mean Site Index error, the 300 Index values, the error standard deviations and error correlation from the nested analysis of variance using the bivariate normal distribution. The errors were added to expected site productivity values for both a low productivity and a high productivity site. The low productivity site had a Site Index of 23.4m and a 300 Index of 27 $m^3 \cdot ha^{-1} \cdot yr^{-1}$. The high productivity site had a Site Index of 29m and a 300 Index of 37 $m^3 \cdot ha^{-1} \cdot yr^{-1}$.

Writing Forecaster files

For the second step of the process Forecaster project files were generated in R to match Forecaster project file formats. A Forecaster project is made up by 10 csv files; a Project file, Site file, Crop file, Function Set file, Species file, Regime file, Log Product Definition file, Cutting Strategy file, and a Report Options file. These were generated with correct column headings to match the Forecaster requirements for importing. Parameters for the productivity and tending regime were included in the file content, and all 10 files were saved in the same directory. For the crop and regime files to be compatible the silviculture in each must align; that is the measurement date in the crop file must occur before the first silvicultural treatment of the regime and the decline in tree stocking overtime across the two files should represent the rate of tree mortality. The Forecaster program provides a function for generating starting values automatically for projects created through the GUI. To reverse engineer this function for the automated runs for this model a series of simulation projects were created. The age of first measurement, crop size and coefficient of variation for DBH and MTH were predicted from these projects with simple linear regression using mapped Site Index and 300 Index as explanatory variables. The resulting functions were implemented in the R code to predict the earliest possible starting age able to capture variation in the stand and the corresponding crop parameters for diameter and height. Implementing these functions enabled automatic production of crop files as part of the stochastic process.

Two regimes were simulated; an appearance regime and a structural regime. The timing of silviculture for these is shown in **Table 4-1**. A binomial process was used to decide if a given simulation run would follow an appearance or structural regime, with the probability set to 50% each way so that both pruned and unpruned regimes were included in the wind damage allocation later in the modelling process. The specific models implemented in Forecaster to simulate tree growth were chosen to be the most up to date for radiata pine and representative for a Central North Island forest, and are presented in Table 4-2. Once the initial forest modelling is complete a harvest and the associated log bucking is simulated in Forecaster and the log grades used in the simulated harvest are shown in **Table 4-3**.

Table 4-1: Forest regimes to be modelled in Forecaster

Radiata pine appearance grade regime
Plant 833 sph
Prune 400 sph to 2.4m at DOS 16cm with minimum green crown remaining 3.5m.
Thin to waste to 375 sph
Prune 360 sph to 4.3m at DOS 17cm with minimum green crown remaining 3.5m.
Prune 360 sph to 6m at DOS 17cm with minimum green crown remaining 3.5m
Thin to waste to 360 sph
Clearfell at 28 years

Radiata pine structural regime
Plant 1000 sph
Thin to waste to 450 sph at MTH 8
Clearfell at 28 years

Table 4-2: Forecaster model inputs used to simulate forest crop type growth.

Growth model	300 Index Regional drift factor: -0.05 Mortality adjustments: 0
Monthly adjustment	2 (Kaingaroa 1985)
Height/age table	112 (mandatory for 300 Index)
DOS function	DOS1999
Sweep model	Generic
Forking model	Generic
Carbon model	C-Change **(Beets et al., 2011)** Clearfell percent: 85 Needle retention score: 2.1
Density Model	WQI Basic Density BHOWD: (or mean air temp)
Volume table	460 (All NZ 3-point)
Taper table	460 (All NZ 3-point)
Breakage table	17 (KANG 1997)
Branch model	Blossim **(Grace. 1999)**

Table 4-3: Log grades to be used for forest growth simulation[8]

Log Grade	Log status	Small end Diameter (mm)	Maximum Knot (mm)	Sweep (% dia/m)
Large pruned	Pruned	400+	0	5.9
Medium pruned	Pruned	300-399	0	5.9
Large unpruned, small branches	Unpruned	400+	60	5.9
Medium unpruned, small branches	Unpruned	300-399	60	5.9
Small, small branches	Pruned or unpruned	200-299	60	5.9
Large, large branches	Unpruned	400+	140	5.9
Medium, large branches	Unpruned	300-399	140	5.9
Small, large branches	Unpruned	200-299	140	5.9
Pulp	Unpruned	100	n/a	47

Running initial simulations

Project files were imported into Forecaster by manually opening the Forecaster program through the GUI and selecting the project file. Once files were imported the rest of the process was automated, including rewriting the Forecaster files for simulating wind damage and restarting those simulations. The automated process used a Microsoft Windows batch file to instruct Forecaster to run the imported Forecaster project files. Once the import process finished the batch file was executed and the modelling process was left to complete. A series of 1000 simulations made up by an approximate 50 percent split between appearance and structural regime simulations. One run of 1000 simulations would typically take 8 hours on a standard laptop computer. The CSV results files from Forecaster were written to a designated location for R to access for the next process.

Applying wind and fire

Following the initial simulations Forecaster results in the designated folder were imported into R. The stand average tree size metrics were used to produce an annual stand average wind risk index for each run. The wind risk index is calculated using some key assumptions and implemented using

[8] Prices used were based on specifications and long term prices from the Ministry for Primary Industries at Ministry for Primary Industries Log Grade Specifications, Online Reference. [Accessed 29/10/2012] http://www.mpi.govt.nz/news-resources/statistics-forecasting/forestry/log-grade-specification.aspx.

the findings from chapter 2 - "Catastrophic damage". The index was adjusted to match the regional probability for catastrophic wind damage from Moore, Manley et al. (2011) and used as the probability of wind failure. Once simulations were selected for wind then additional plots were selected for fire damage in a similar manner to match the annual probability for file found by Anderson, Doherty et al. (2008) except the annual probability for the chance of fire was even across simulated stands and ages. Further detail on the selections for wind and fire is described under the following headings:

Wind risk

The effects of wind throw were modelled in Forecaster by simulating an early harvest event using an adjustment to the log grade outturn and increased harvest costs. The probability of a stand suffering wind damage was calculated annually by comparing the maximum resistive bending moment of the tree root systems (m_g) with a maximum likely bending moment applied by wind (m_w). Wind throw or no wind throw was assigned using a single binomial variable with probability based on the difference in these bending moments and adjusted using a coefficient calibrated to the average regional rate of wind throw of 0.21% annually by area (Moore, Manley et al. 2011). The forces and tree metrics considered when calculating the index are labelled in **Figure 4-2**. The two main forces in calculations were m_w and m_g; the moment caused by wind on the tree canopy and the resistive moment provided by the ground.

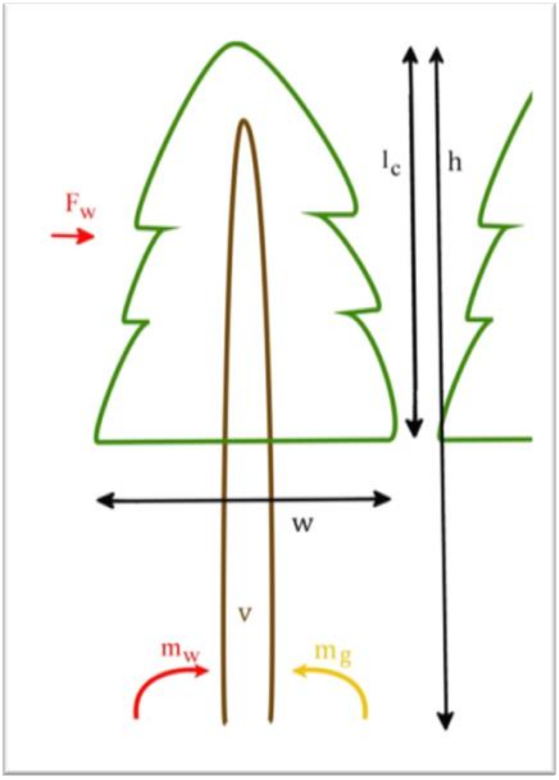


Figure 4-1: Diagram of forces and crown metrics used in wind risk calculation.

The maximum resistive bending moment of the ground was calculated with **Equation 3-1** using stem volume v as the determinant variable. This equation is from Moore and Quinine (2000) was derived from tree winching studies in Kaingaroa forest.

Resistive moment provided by the root system for a tree

$$m_g = e^{0.929\,ln(v)+4.378}$$ **Equation 3-1: (Moore and Quine 2000)**

Where m_g = maximum resistive bending moment

v = stem volume in cubic metres

The formula for the bending moment from wind force on the tree canopy was calculated from tree height produced in Forecaster, a predictive green crown length model and a crown width estimation calculated from average tree spacing. These were used to calculate the coefficient for the bending moment along the stem based on the assumption of a permeable triangular crown sail area. Green crown length (l_c) is defined as the length from the top of the tree to the point half way between the lowest green branch and the first full green whorl (Ellis and Hayes 1997). Green crown length is measured as part of routine PSP measurement, while crown width is not. Because there was no validation data for crown width the coefficients used by Sattler and LeMay (2011) for a linked crown length and width relationship for *Pinus contorta* in the northern hemisphere were considered, but the Northern hemisphere model did not provide an adequate fit for crown length. Instead the simplified crown length equation was re-modelled to fit the case study green crown data. As this model was only used on the available Kaingaroa data set, no separate validation data set was tested. **Equation 3-3** shows the formula used to calculate crown width. This is based on the assumption that at the time of wind damage there will be canopy closure, and so the crown width is directly calculated from tree stocking. From these values the product of triangular crown area and the height of the centre of that triangle were calculated and multiplied together as an index for the maximum turning moment applied by wind force (m_w).

Green crown length as percentage of tree height

$$l_c = 21.1h^{0.328} \times N^{-0.241}$$ Equation 3-2

Crown width

$$w_c = \frac{100}{\sqrt{N + (N \times N_r)}}$$ Equation 3-3

Where: l_c = green crown length as a percentage of total tree height (%)
h = tree height (m)
N = stocking (stems/ha)
w_c = crown width (m)
N_r = relative stocking as a ratio

The moment applied to the tree from wind force was calculated from the wind risk index using a coefficient, adjusting the index so that the difference between the two opposing moments in each year of simulation across all 1000 simulations adds to the combined probability of annual area lost. That is that the difference between the wind moment and the resistive root plate moment matched the average annual percentage area loss to wind throw when averaged across all 1000 simulations, including both structural and appearance regimes. The overall effect is that the average wind throw probability was equal to the measured Central North Island regional probability of 0.21% of production forested area lost to wind damage per year (Moore et al 2011), while tall stands with lower stem volumes and larger crown areas have the higher risk of wind throw. This system enables simulation of windthrow and its effects on carbon sequestration and forest value.

The breakage table used for the harvest simulation was the Forecaster breakage table 1. This original table is from measurements of break heights from felled trees in Kaingaroa Forest in 1976 analysed by Goulding and Deadman. For the wind damaged simulations the average break height was left unchanged at 67% of tree height, on the assumption that average break height is similar between wind throw and manual felling. It was assumed that standard deviation of the break heights is increased during wind throw. This assumption is reinforced by the findings of Knowles and Paton (1989) who found break height averaged around 60% of tree height in a stocking trial at Tikitere, Bay of Plenty, New Zealand after wind throw due to cyclone Bola in 1988, and the observations of Fredricksen and Hedden *et. al.* (1993) who noted high variation in break heights for winched trees. To simulate the effect of the wide variation in break height the waste log grade was increased by 33%, in line with the finding of chapter 2 - "Catastrophic damage". Harvest costs were increased by 33%; a value derived through personal correspondence with an industry expert[9] and in line with previous New Zealand windthrow simulations (Manely and Wakelin 1989, Brown and Bilek 1997) who used a slightly lower value at 25%.

Fire risk

Fire was introduced to the model in a similar manner to windthrow; in that a binomial selection was used and the average probability selection was matched to an average area lost per year of 0.024 percent per year, calculated from the data presented by Anderson, Doherty et al. (2008). However, it was assumed each stand had an even probability of catastrophic damage each year, and there were no adjustments to harvest costs or log grade out turn, as per the findings in the "Catastrophic damage" chapter. The fire damaged simulations lost value because of the earlier harvest timing only.

Summarising the results

Following the wind and fire selections and re-running the damaged simulations the results were saved by Forecaster to the designated folder. The silvicultural event names, the year of the events, harvested log volumes, log values and carbon sequestered were imported back into R for

[9] D, Janett (personal correspondence 9th October 2013, following his presentation at a Canterbury NZIF event).

summarising carbon sequestration and Net Present Values (NPVs) in perpetuity. Sequestered carbon is an output in the Forecaster results, coming from the built in C-change carbon model (Beets, Kimberley et al. 2011). Carbon sequestration from Forecaster is divided into carbon pools; below ground live carbon, above ground live carbon, dead woody litter, and fine litter. The carbon sequestration presented in this research is the total across all four pools. NPVs were calculated from the event timing in the Forecaster results using the costs in **Table 4-4**. To calculate NPVs in perpetuity costs and revenues were repeated 500 times. A large number of replications were chosen to ensure that if a series of consecutive runs had windthrow in the early stages of the rotation there would still be enough replications to approach the correct present value to represent perpetual rotations. For each replication of the cost and revenue table the order of cost and revenue columns was randomly rearranged, so that each subsequent simulated rotation had an equal chance of the following a wind damaged rotation. The process of cost and revenue replication and rearranging was repeated 5 times and averaged to average the effect of the order of wind damage occurrence early in the NPV in perpetuity calculations.

Table 4-4: Costs used in Net Present Value calculations

	Costs	Unit	Year of Operation	
			Structural Regime	Appearance Regime
General costs				
Site prep	80	\$/ha	-1	-1
Dothi Spray	60	\$/ha	4, 8	4, 8
Annual costs				
Admin	5	\$/ha	every year	every year
Land rent	275	\$/ha	every year	every year
Event costs				
Planting	350	\$/ha	0	0
Planting stock	0.7	\$/seedling	0	0
Thinning	380	\$/ha	MTH = 8m	DOS = 16cm
Prune 1	720	\$/ha	N/A	DOS = 16cm
Prune 2	380	\$/ha	N/A	DOS = 17cm
Prune 3	340	\$/ha	N/A	DOS = 17cm
Harvesting costs				
Roading	2000	\$/ha	Harvest	Harvest
Harvesting (Ground based)	25	$\$/m^3$	Harvest	Harvest

NPVs and Carbon sequestration were presented in a histogram to show the shape of the distributions of value and carbon sequestration of the simulated stand type and give insight into the confidence in estimations of the parameters. Key variables of interest including means and standard deviations were presented inside the graphs to display significant details of the simulated distributions.

For NPV the model was run on the structural and appearance regimes on both high productivity and low productivity sites typical of the Central North Island forest area, both with and without catastrophic damage for 1,000 hectare stands only. For carbon sequestration the model was run on the structural and appearance regimes on both high productivity and low productivity sites typical of the Central North Island forest area, both with and without catastrophic damage for 1,000 hectare and 10,000 hectare stands. This resulted in 6 simulations, with 12 carbon sequestration distributions. The results show the contribution of uncertainty in the prediction of productivity indices and the contribution of catastrophic damage to variation in the estimation of forest value and carbon.

Results

The results section is split into three sections. The first focuses on the intermediate models within the modelling system predicting crown metrics and probability of windthrow. The second and third sections present the results of the stochastic modelling system, first for carbon sequestration then for NPV.

Intermediate models

The intermediate models include predicting the green crown length and crown width, which is then used to predict the probability of windthrow for each simulated year of forest growth. Predicting the green crown length was done using a non-linear relationship with stocking and a linear relationship with MTH. The combined function provided the green crown length model with a good estimate of fit and a nice pattern in the residuals as can be seen in **Figure 4-3**. While both green crown length and crown width were predicted for wind damage simulation, only green crown length was recorded in the PSP data so only crown length could be validated. **Equation 3-2** shows the predictive model for green crown length as a percentage of tree height. This model explained 82.6% of the variation in green crown length and **Figure 4-3** shows a plot of this model with residuals indicating a good fit to the data.

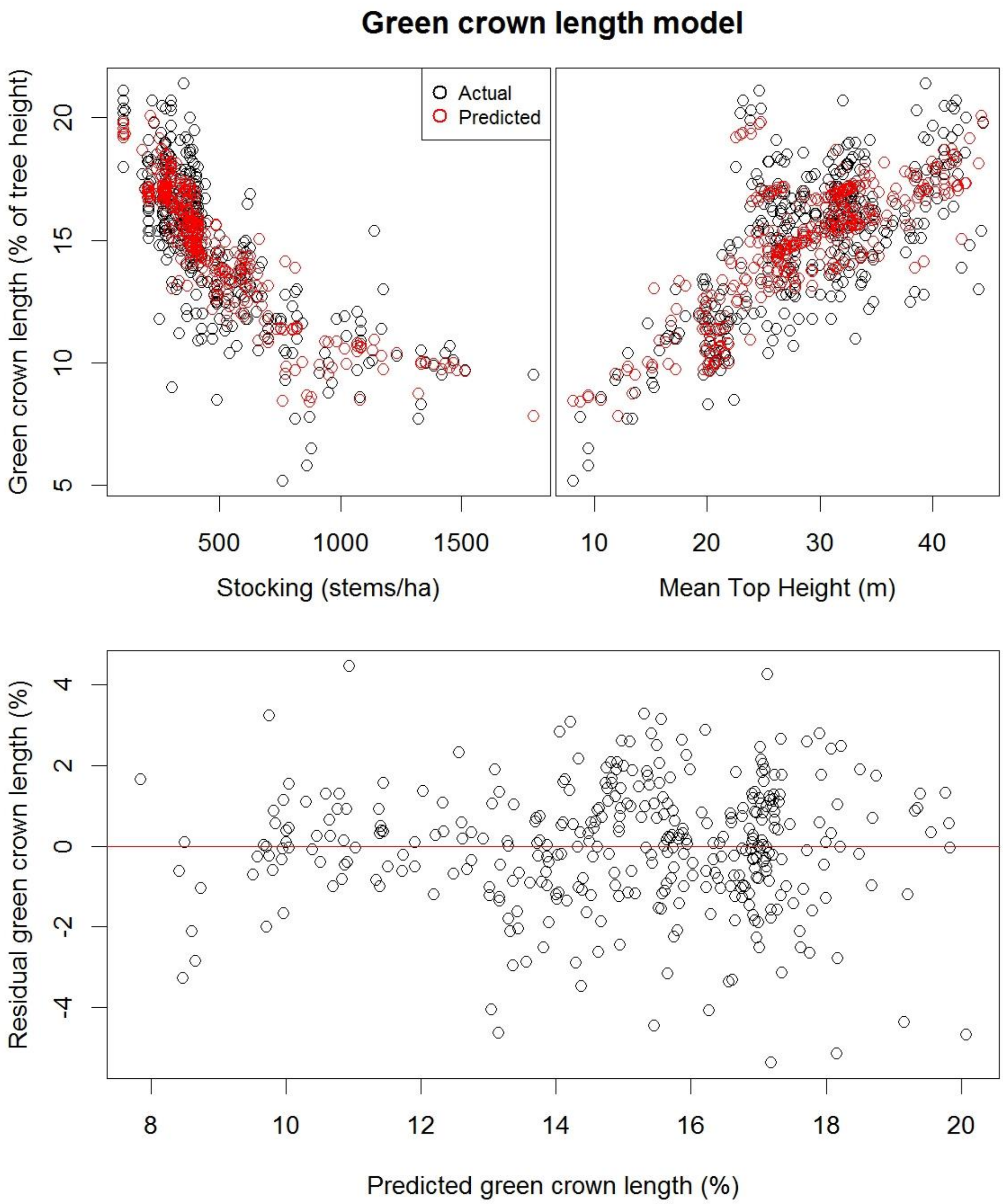


Figure 4-3: The model used to predict green crown length, to be used as an input for calculating the risk of wind damage as a component for tree sail area.

The probability of wind throw was calculated from stand metrics. The probability of windthrow was derived from the difference between the resistive moment provided by the root plate and the moment created by the sail area of the crown and the height of the tree in the wind. The progression of the probability of wind throw for a selection of simulations both in an appreaance and structural regimes is shown in **Figure 4-4**. The general trend is for increasing risk of windthrow with age and a jump in the probability of wndthrow immediately following silviculture. The jump in probability is driven by stocking after thinning, when the stocking is reduced and the trees have a larger exposed sail area.

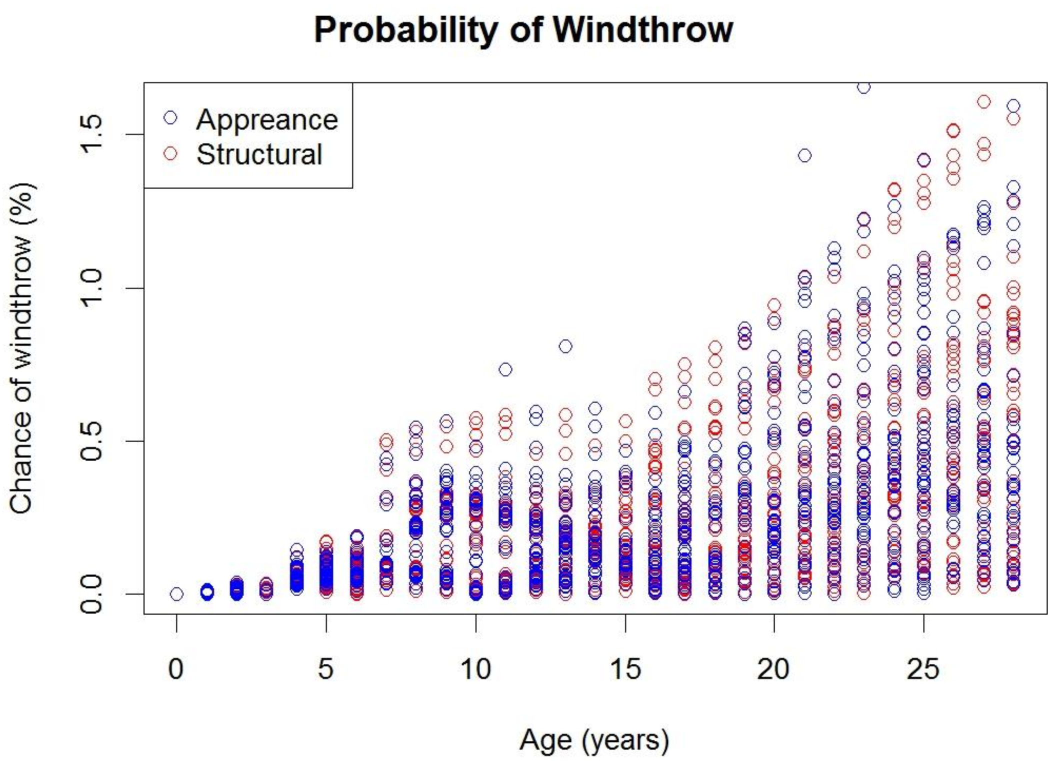


Figure 4-4: Chance of windthrow overtime for a selection of appearance and structural regime simulations.

Carbon sequestration

Carbon sequestration was modelled on high productivity and low productivity sites, with and without wind and fire damage and on 1,000ha and 10,000ha stands. **Figures 4-5** to **4-16** show the combinations of simulations over those combinations. Each pair of figures is arranged with a structural regime above an appearance regime on one page, starting with low productivity sites then high productivity sites. **Figures 4-5** to **4-8** show simulations without wind damage, and are followed by **Figures 4-9** to **4-12** showing simulations with wind damage.

Each chart shows the distribution of probable volumes of carbon sequestered with a histogram and a probability density function. For reference the expected value is included, which is the carbon sequestered which would have been calculated by conventional deterministic methods.

Figures 4-5 and **4-6** show a low productivity site with no wind or fire damage included in the simulation. This is followed by **Figures 4-7** and **4-8** which show a high productivity site with no wind or Fire damage. Both the low productivity site and high productivity site simulations have a similar shape of distribution. All simulations without wind damage are approximately normally distributed and the predicted standard deviations give a good indication of the uncertainty around the mean. The confidence intervals for carbon on both the low and high productivity sites excluding any effect from wind damage were all under 10% of the mean estimated carbon sequestered. The high productivity site provides a 20% higher carbon yields immediately prior to harvest across both the structural and appearance regimes.

Figures 4-9 to **4-12** repeat the simulations of **Figures 4-6** to **4-9** but with catastrophic damage from wind and fire included. The addition of catastrophic wind and fire damage created a long tail on the distribution spreading the distribution out further to the left by significantly lowering the carbon sequestered at harvest for a small selection of simulations. The distribution produced is highly skewed and this shape does not fit a normal distribution, and as such the confidence intervals predicted in the figures do not represent the effect of the uncertainty from catastrophic damage. The calculated 95% confidence interval assuming a normal distribution with wind and fire damage is around 20% of total sequestered carbon for low productivity sites and slightly lower at 19% of total carbon sequestered for high productivity sites. The inclusion of wind and fire damage at 0.21% and 0.024% respectively by area lowered the average estimated carbon sequestration for structural regimes by 5% while appearance regimes were lowered by 3%. Due to the variance in the simulations these decreases were not statistically significant.

Figures 4-13 to **3-16** show the wind damaged simulations repeated over larger 10,000 hectare stands. As with the generated productivity indices in chaper2 - “generating productivity indices”; there was no significant effect of area. The minor effects observed in the productivity indices generation from area were lost in the growth modelling process and the 10,000 hectare simulations show similar trends to those evident in **Figures 4-9** to **4-12** for simulations of the 1,000 hectare stands.

Figure 4-5: **Low productivity, no damage, structural regime over 1,000ha:**

Total carbon sequestration prior to harvest

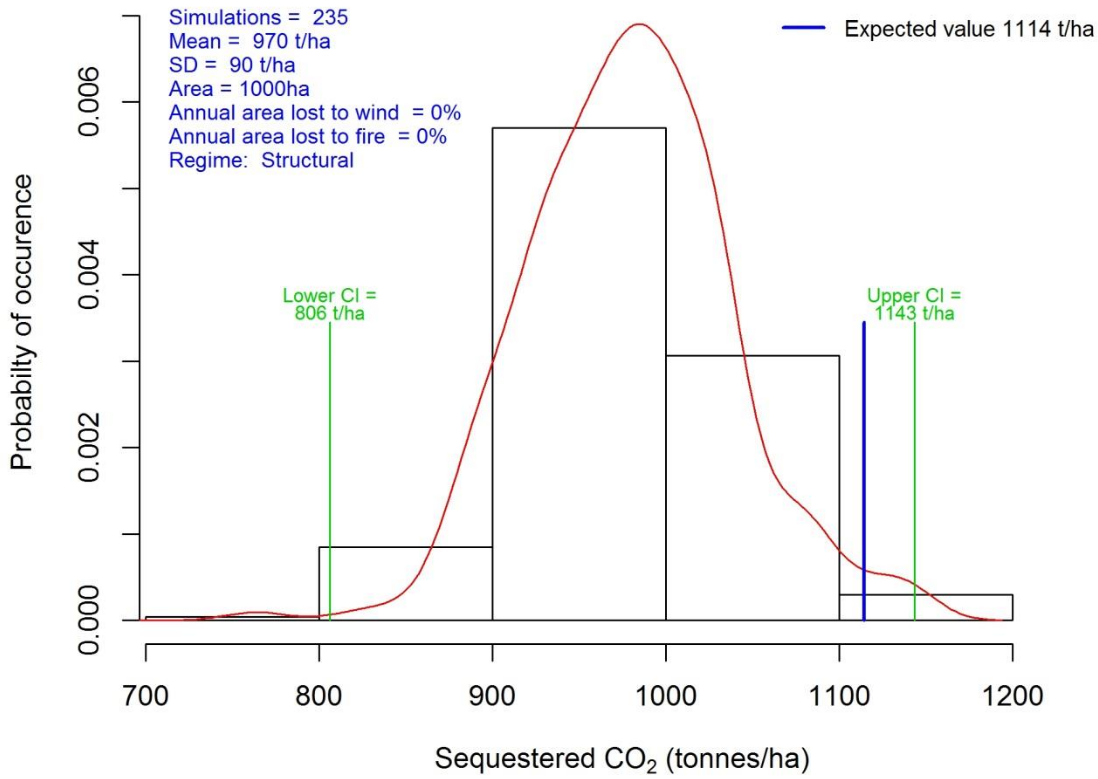


Figure 4-6: **Low productivity, no damage, appearance regime over 1000ha:**

Total carbon sequestration prior to harvest

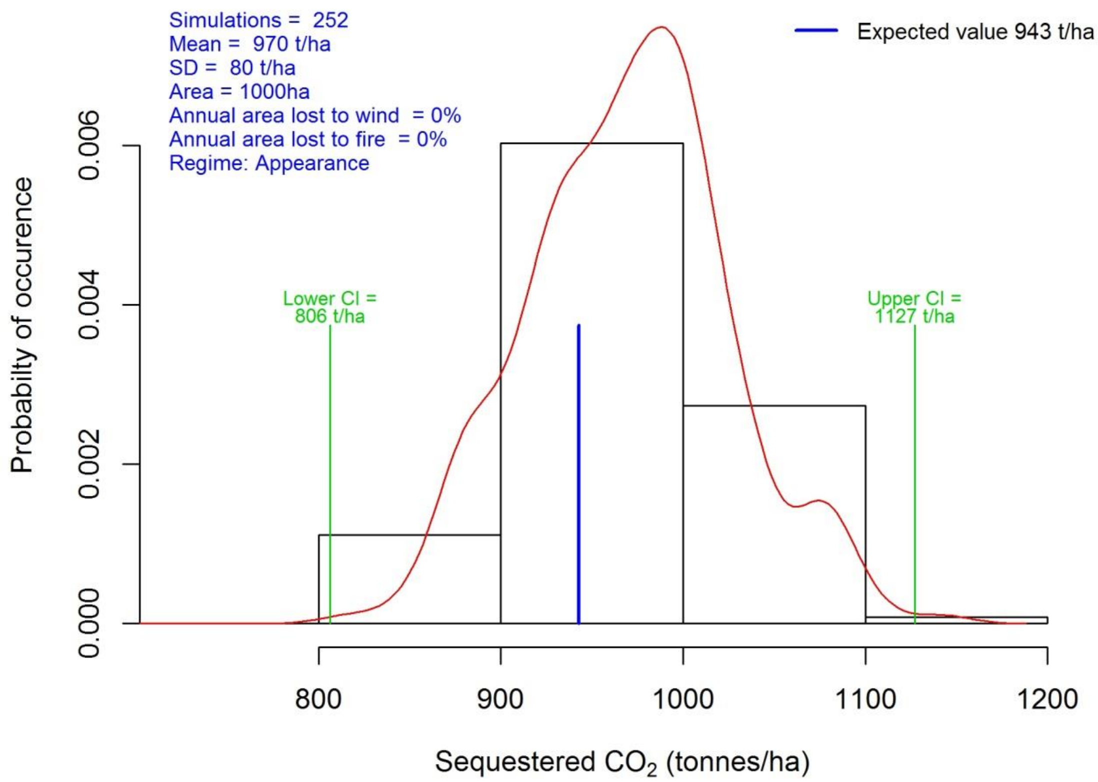


Figure 4-7: High productivity, no damage, structural regime over 1,000ha:

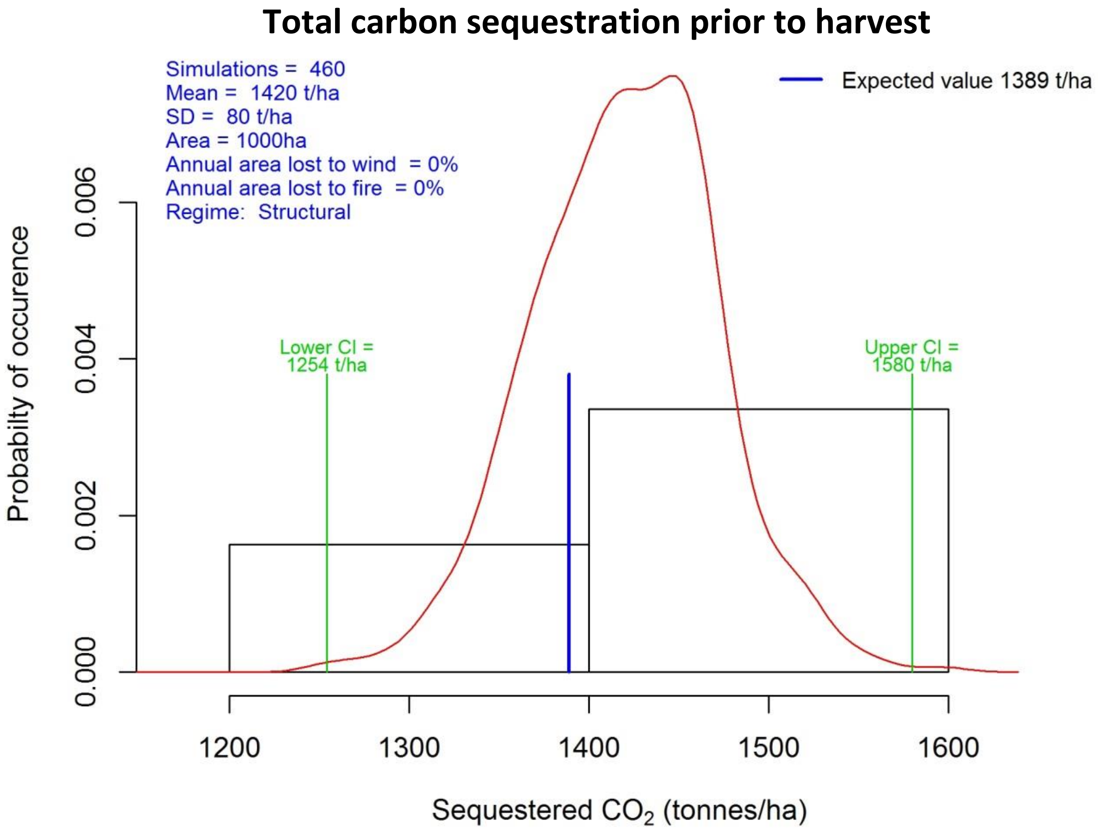


Figure 4-8: High productivity, no damage, appearance regime over 1,000ha:

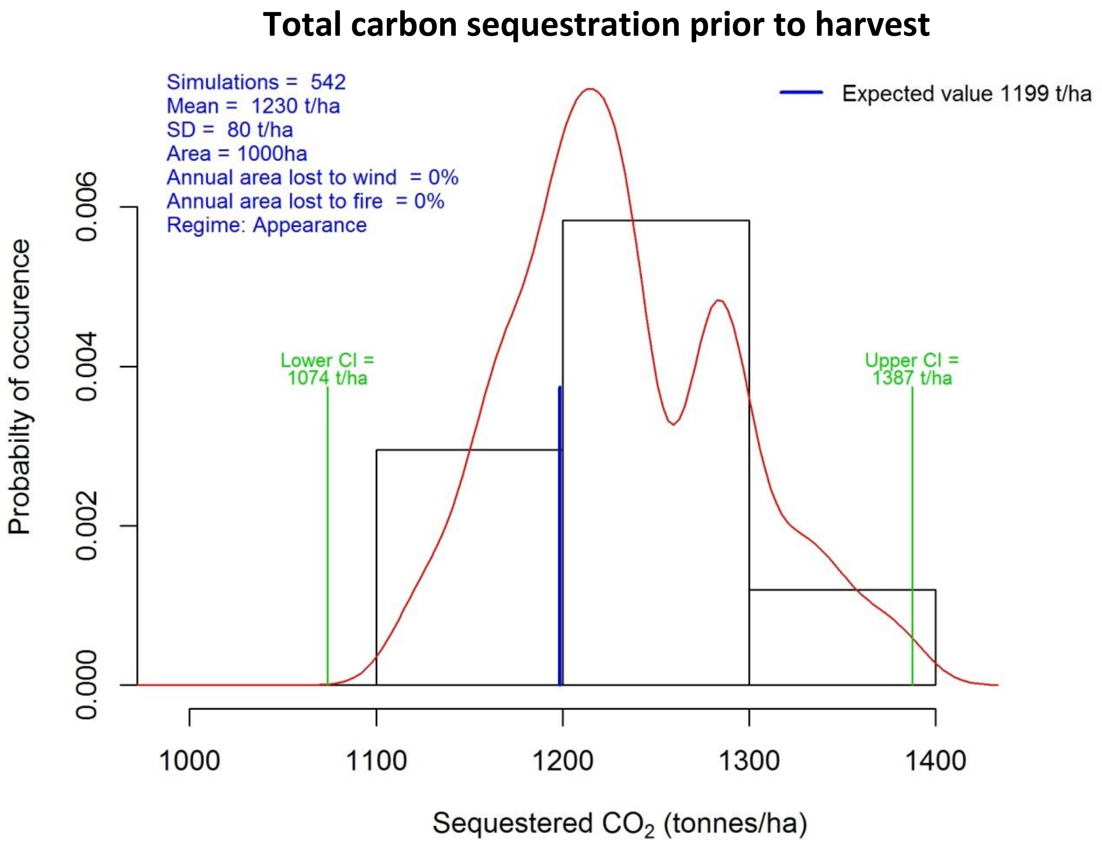


Figure 4-9: **Low productivity, with damage, structural regime over 1,000ha:**

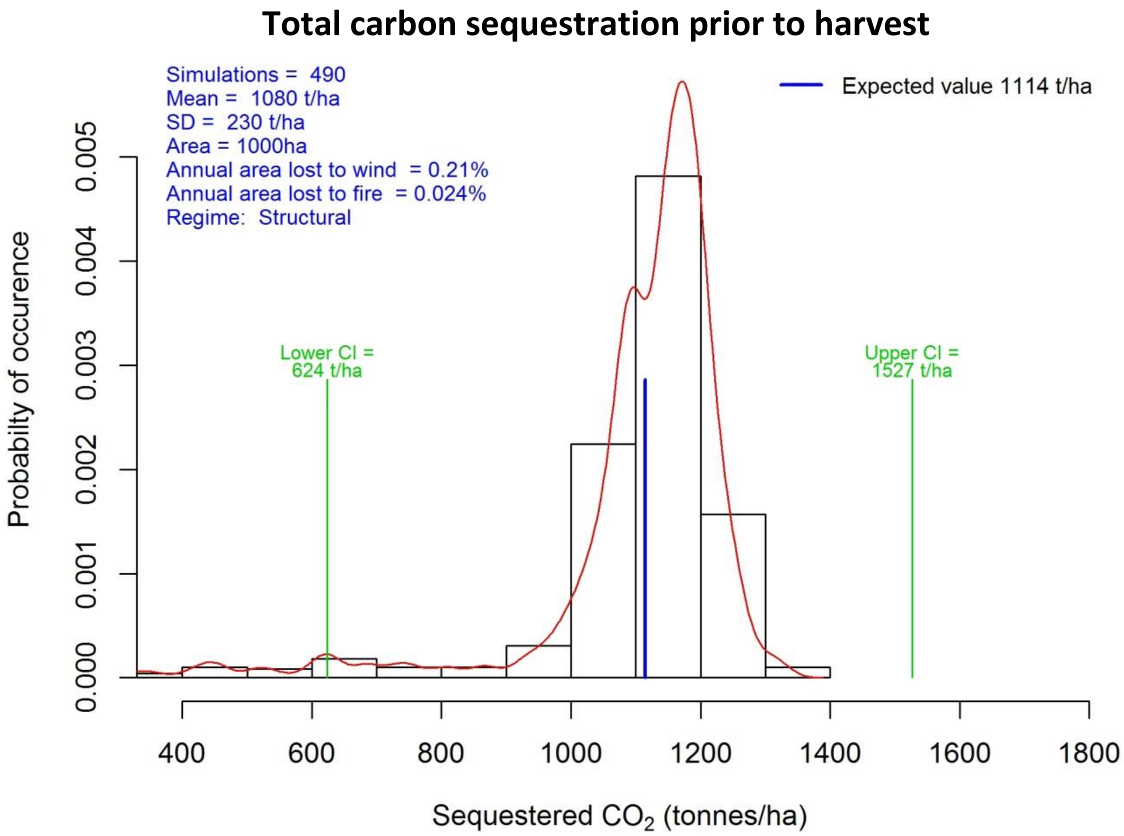


Figure 4-10: **Low productivity, with damage, appearance regime over 1,000ha:**

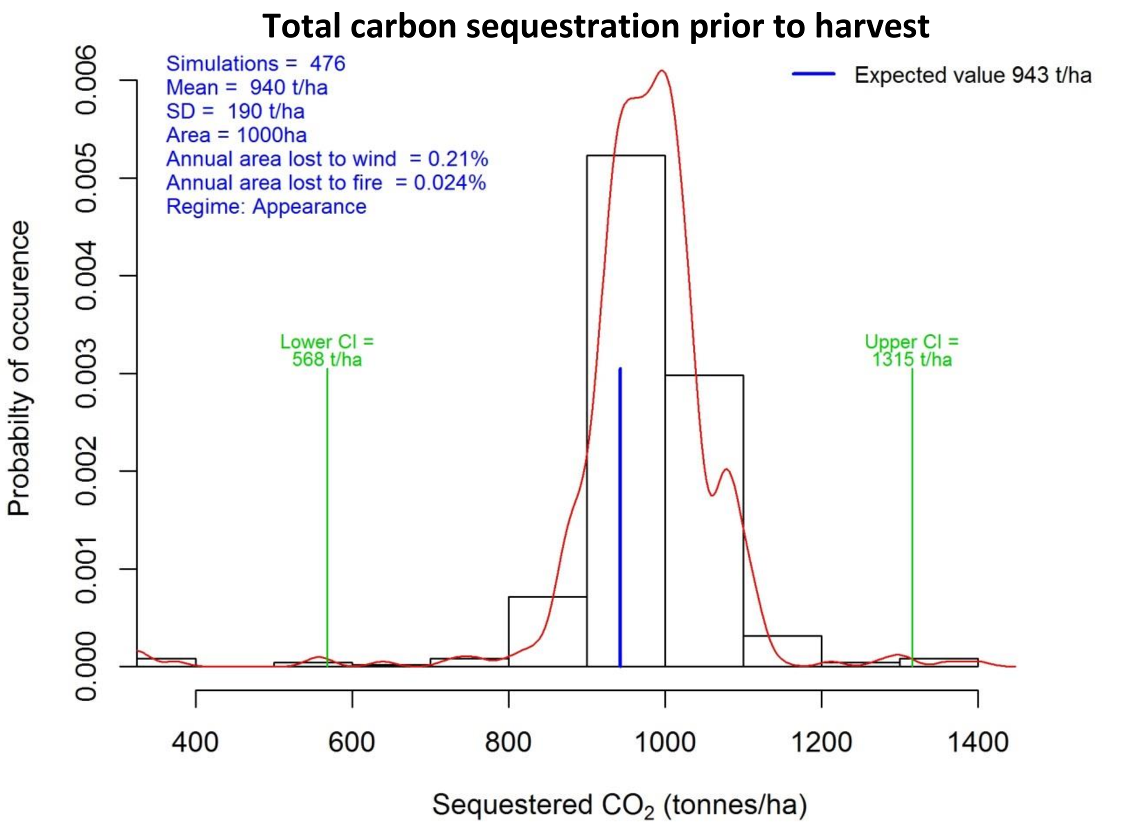


Figure 4-11: **High productivity, with damage, structural regime over 1,000ha:**

Total carbon sequestration prior to harvest

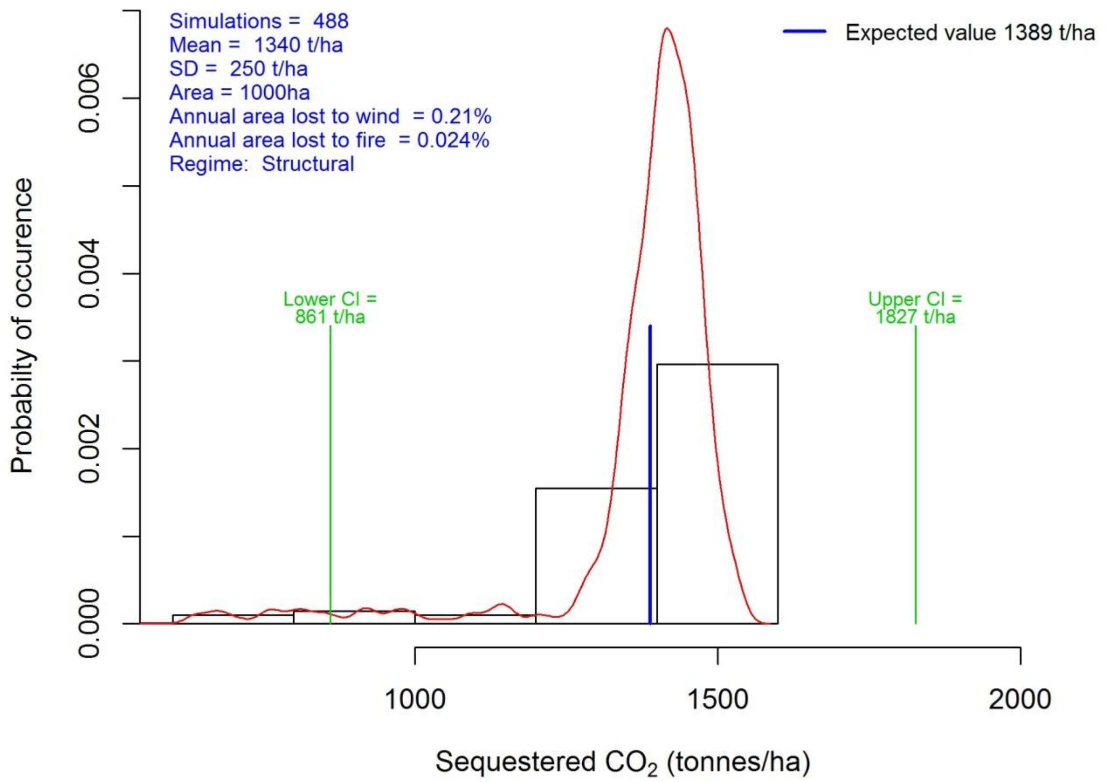


Figure 4-12: **High productivity, with damage, appearance regime over 1,000ha:**

Total carbon sequestration prior to harvest

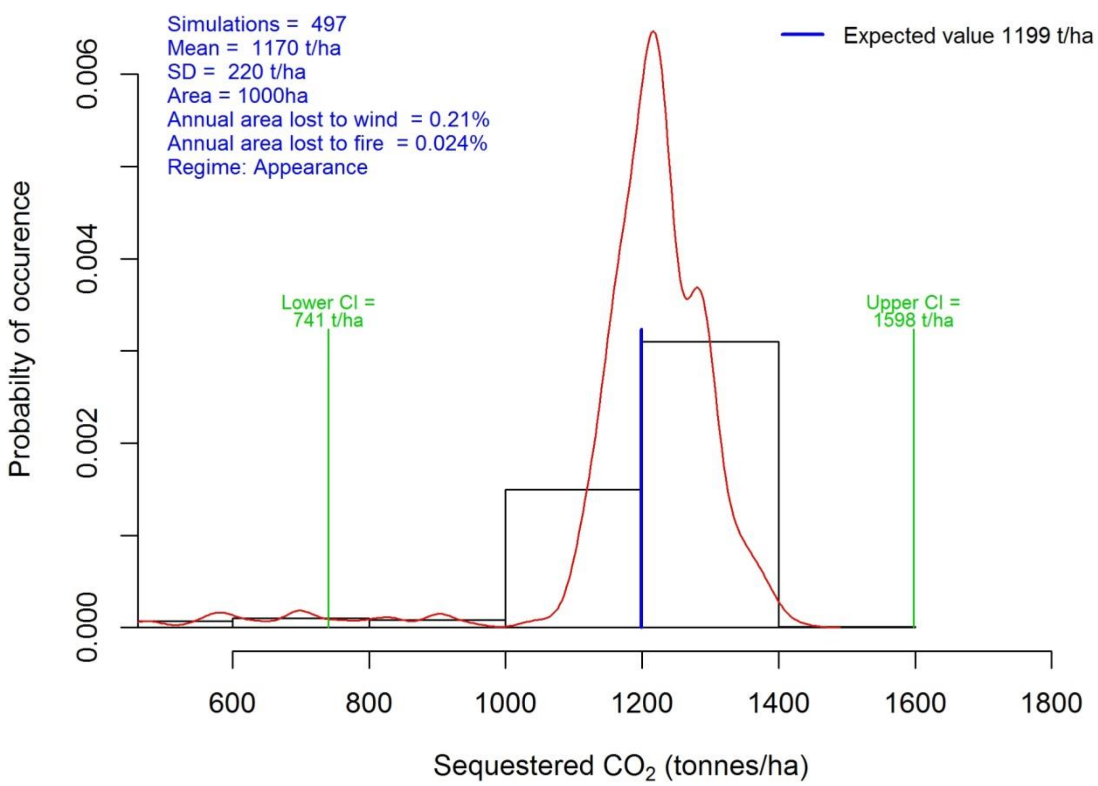


Figure 4-13: **Low productivity, with damage, structural regime over 10,000ha:**

Total carbon sequestration prior to harvest

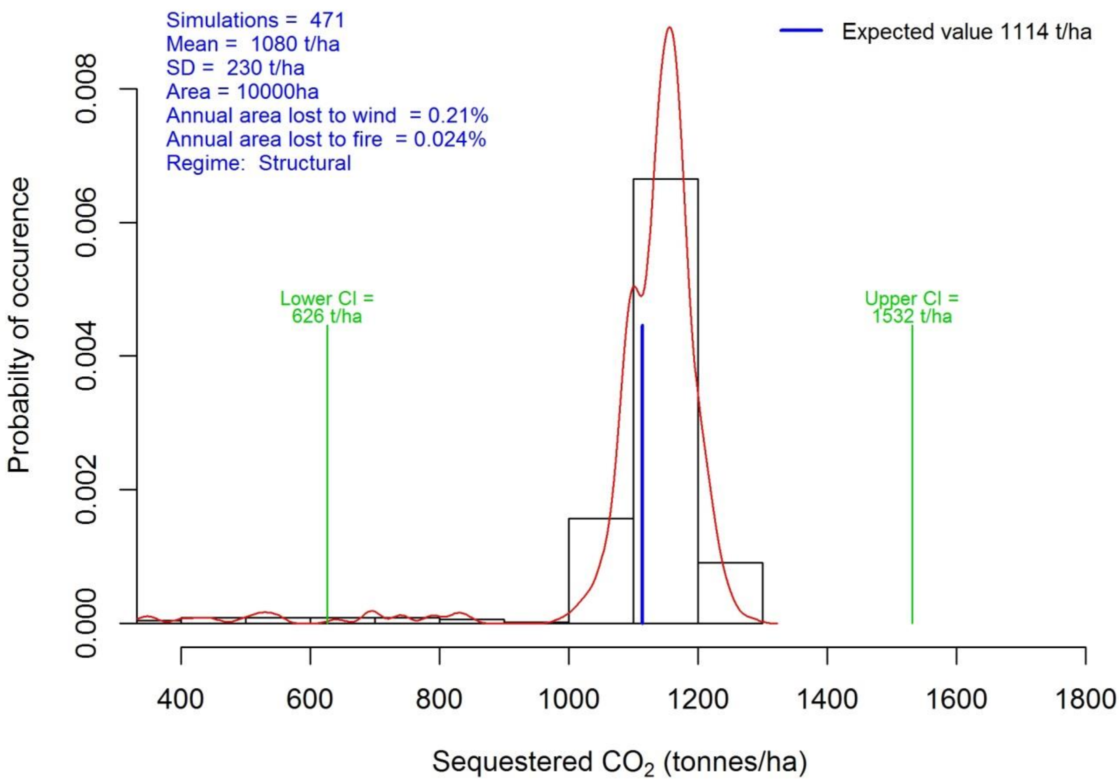


Figure 4-14: **Low productivity, with damage, appearance regime over 10,000ha:**

Total carbon sequestration prior to harvest

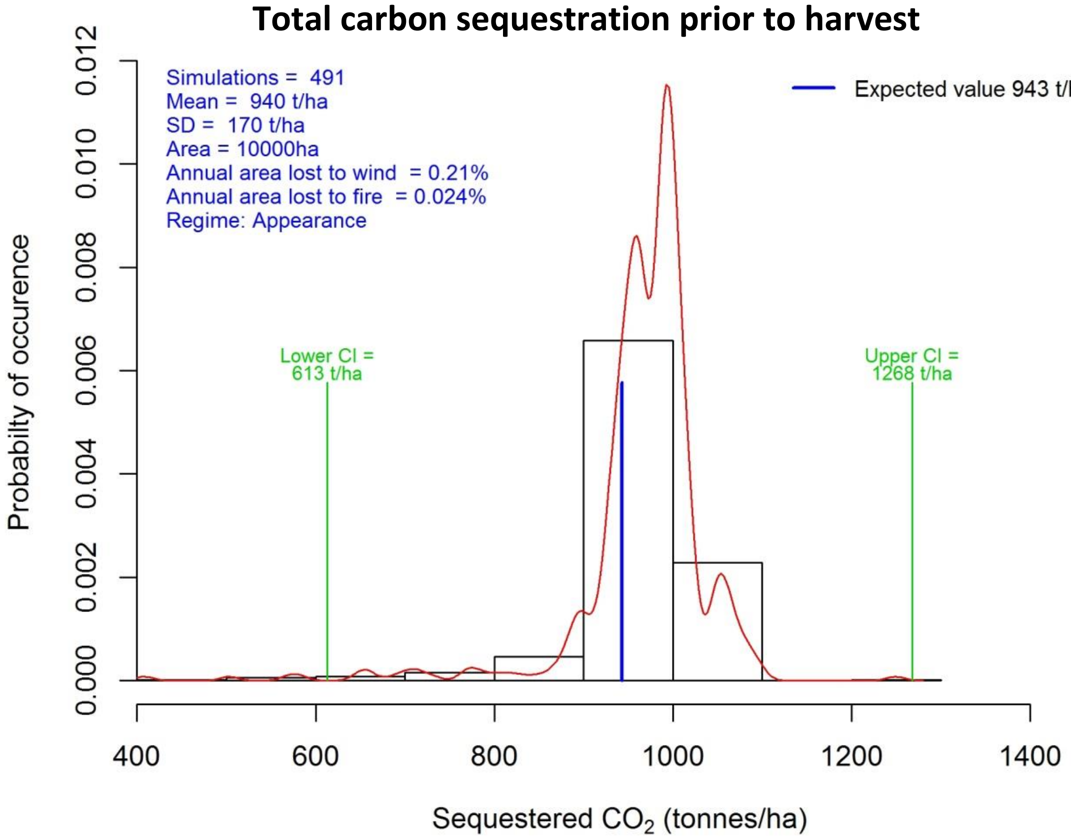


Figure 4-15: **High productivity, with damage, structural regime over 10,000ha:**

Total carbon sequestration prior to harvest

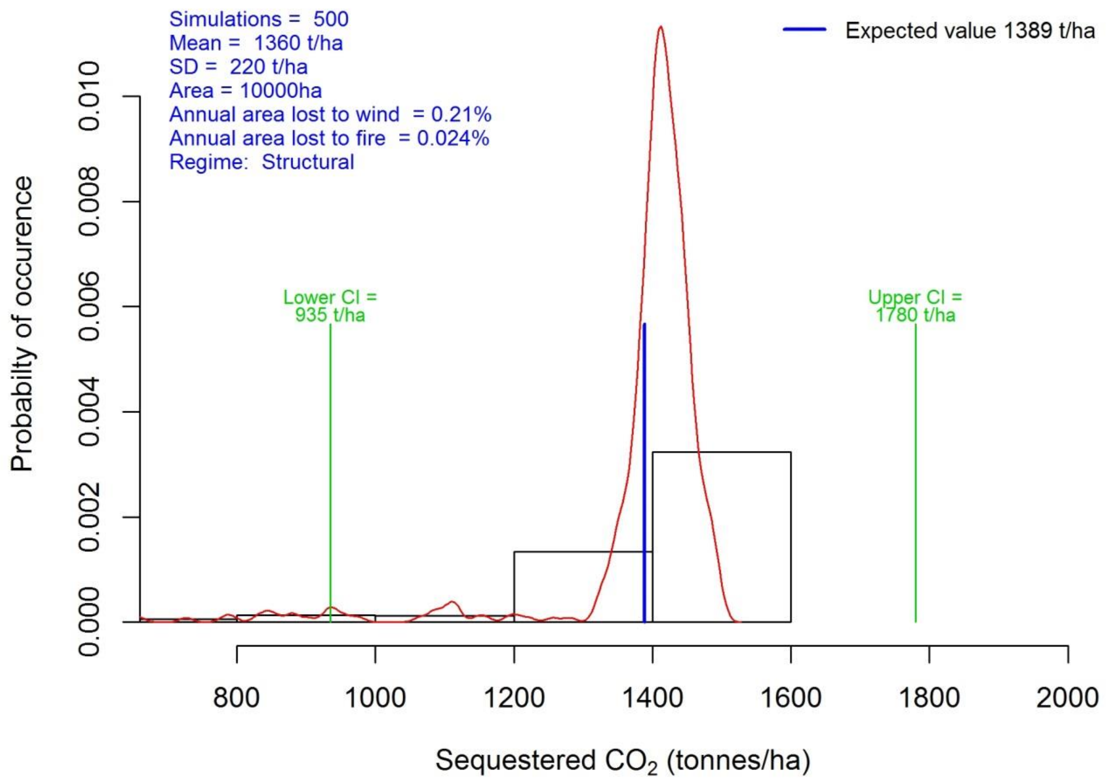
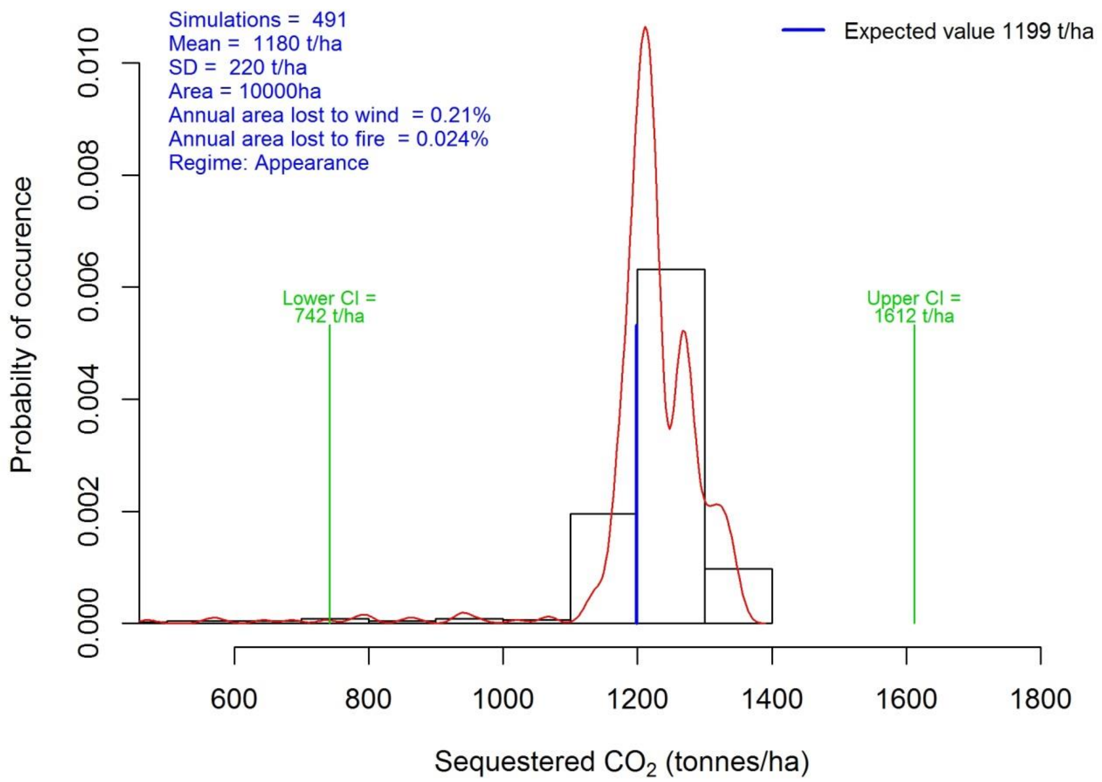


Figure 4-16: **High productivity, with damage, appearance regime over 10,000ha:**

Total carbon sequestration prior to harvest



Net Present Values

As with carbon sequestration NPV was modelled on high productivity and low productivity sites, with and without wind and fire damage, but on 1,000ha stands only. The effect of area is insignificant for carbon sequestration and so NPV was not analysed on the 10,000 hectare larger stands. **Figures 4-17** to **4-24** show the combinations of simulations over the NPV simulation matrix. Each pair of figures is arranged with a structural regime above an appearance regime on one page, starting with low productivity sites then high productivity sites. **Figures 4-17** to **4-20** show simulations without wind and fire damage, and are followed by **Figures 4-21** to **4-24** showing simulations with wind and fire damage.

Each chart shows the distribution of probable NPVs in perpetuity with a histogram and a probability density function. For reference the expected value is included, which is the NPV which would have been calculated by conventional deterministic methods.

Figures 4-17 and **4-18** show NPV for a low productivity site with no wind or fire damage included. This is followed by **Figures 4-19** and **4-20** which show a high productivity site with no wind or Fire damage The low productivity sites produced a very small mean of $160 per hectare for structural and a negative value of -$810 per hectare for the appearance regime, while the high productivity sites were both positive at $2820 per hectare for structural and $690 per hectare for appearance regimes. All simulations without wind damage are approximately normally distributed and the predicted standard deviations give a good indication of the variation around the mean. The confidence intervals for NPV are large. Confidence intervals for all combinations of site and silviculture included zero except for the structural regime on a high productivity site which had a 95% confidence interval from $2056 per hectare to $3579 per hectare.

Figures 4-21 to **4-24** repeat the simulations of **Figures 4-17** to **4-20** but with catastrophic damage from wind and fire included. The addition of wind at a rate of 0.21% annually by area and fire at

0.024% annually by area created a tail on the distribution spreading the distribution out further to the left by significantly lowering the NPVs for a small selection of simulations. The distribution is skewed and this shape does not fit a normal distribution. As such the confidence intervals predicted in the figures do not represent the effects of the variation. The addition of wind and fire damage at 0.21% and 0.024% respectively by area lowered mean NPVs by between no loss and $1200 per hectare. The largest loss from catastrophic damage occurred in the structural regime on the high productivity site with a mean loss of $1260 per hectare or 45%. However due to the large variance in the NPV estimates the differences between simulations with and without damage from wind and fire were not statistically significant.

Figure 4-17: **Low productivity, no damage, structural regime over 1,000ha:**

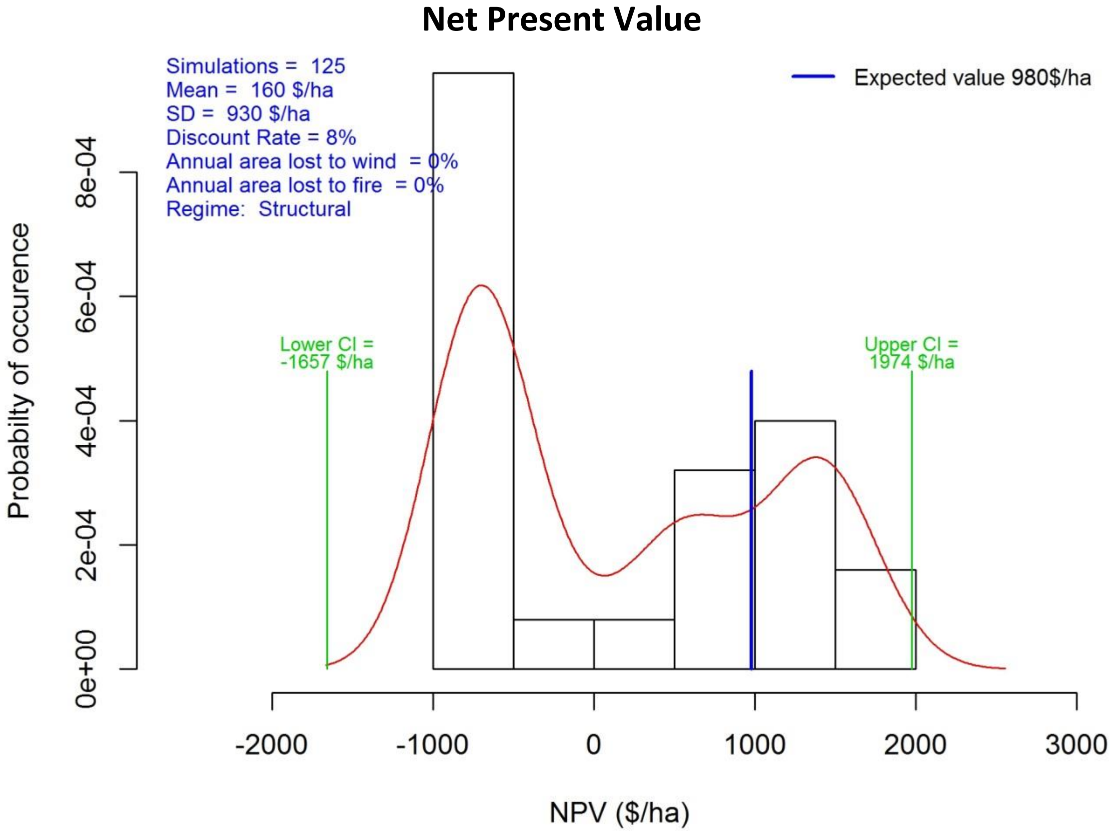


Figure 4-28: **Low productivity, no damage, appearance regime over 1,000ha:**

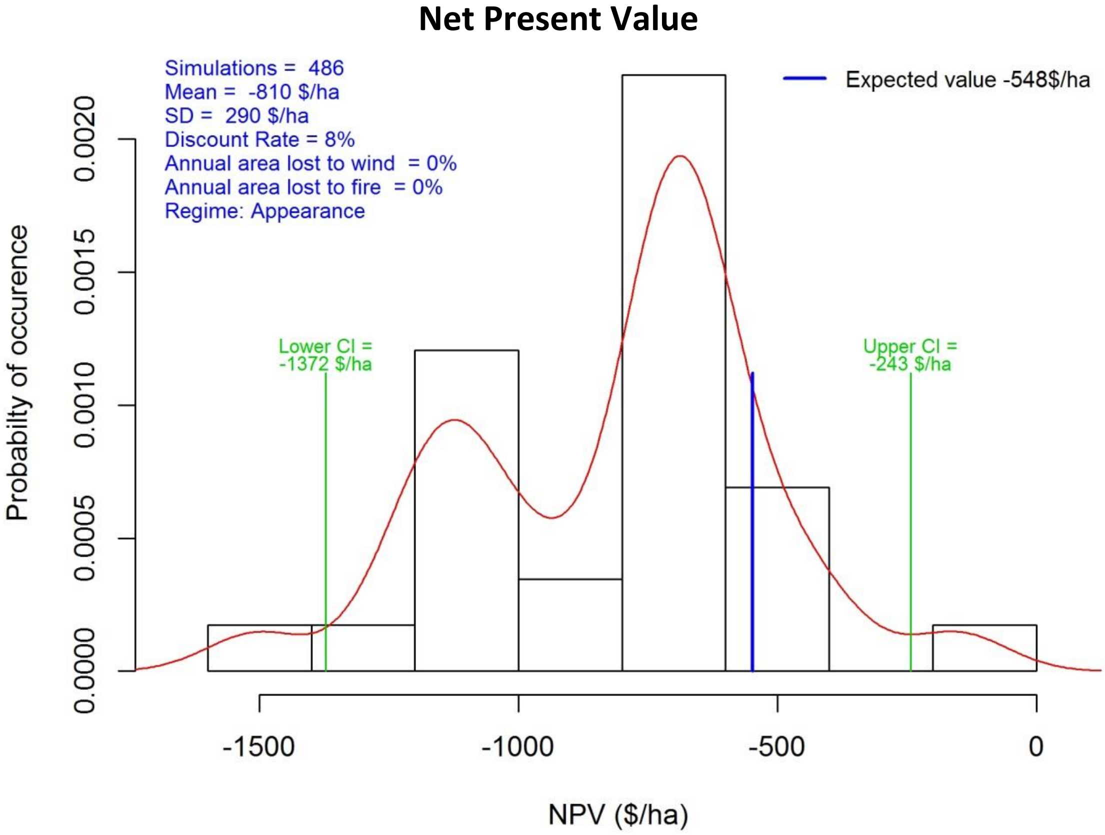


Figure 4-19: **High productivity, no damage, structural regime over 1,000ha:**

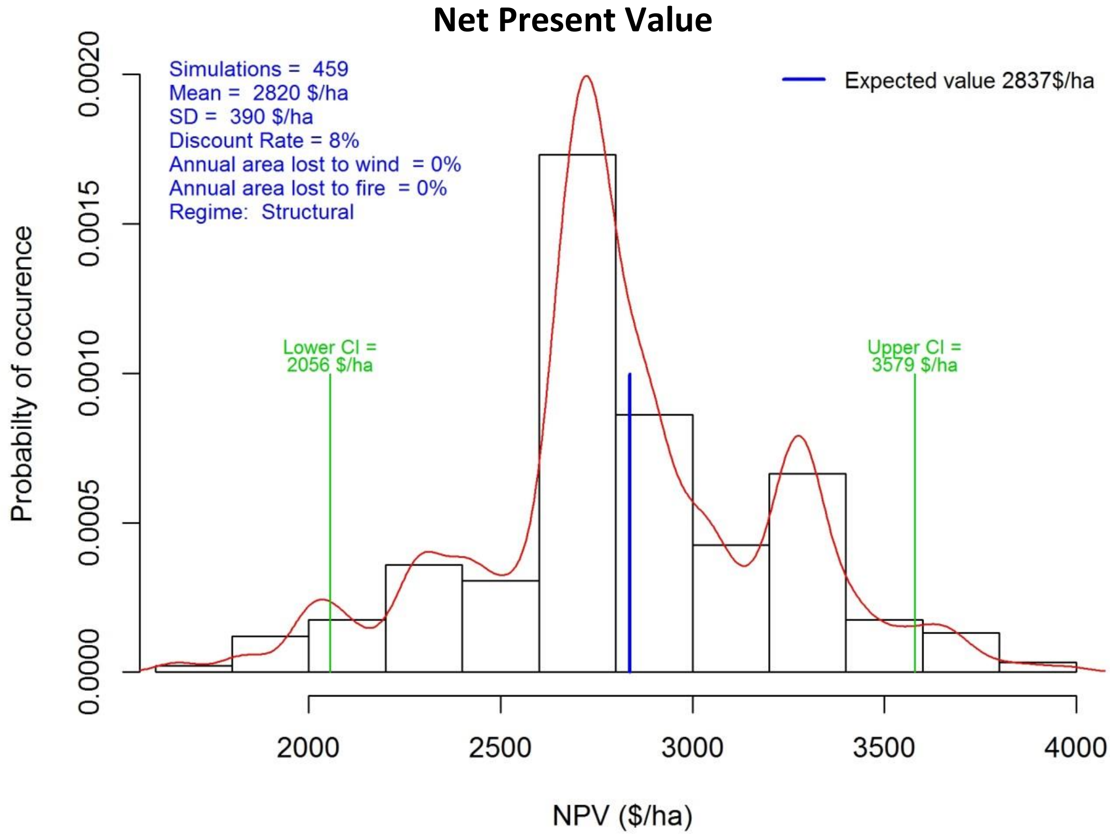


Figure 4-20: **High productivity, no damage, appearance regime over 1,000ha:**

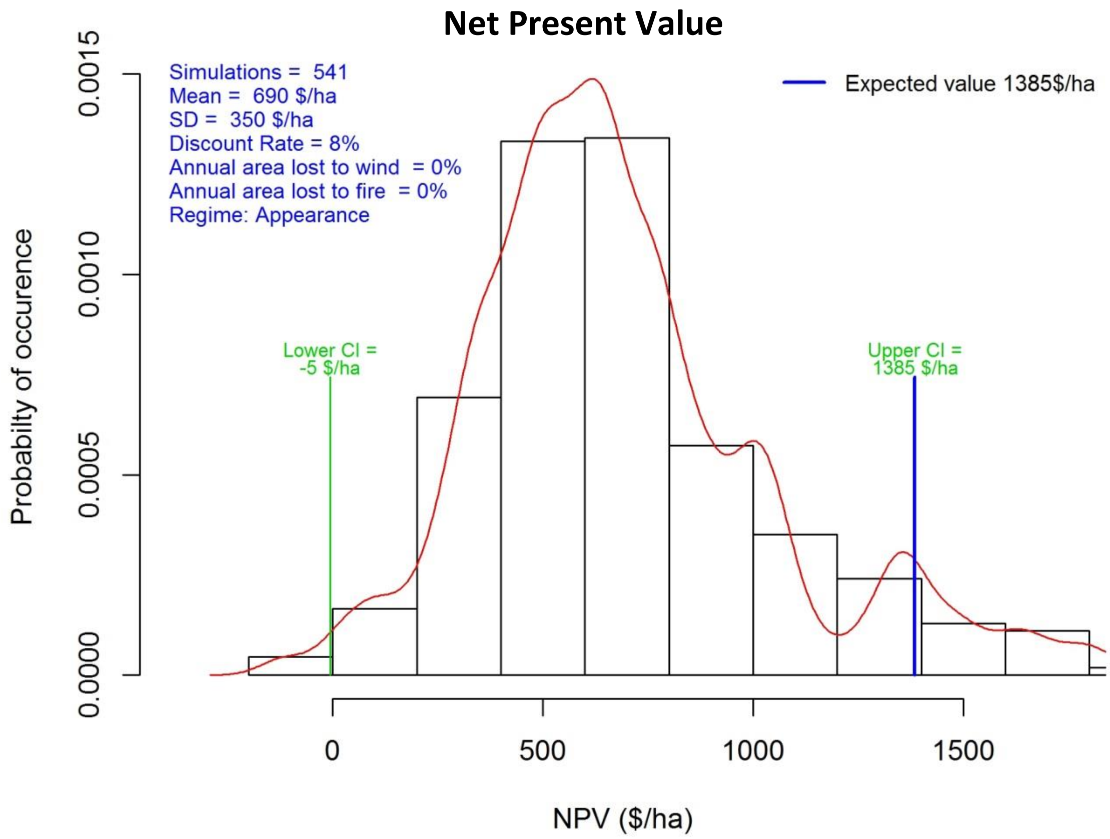


Figure 4-21: **Low productivity, with damage, structural regime over 1,000ha: Net Present Value**

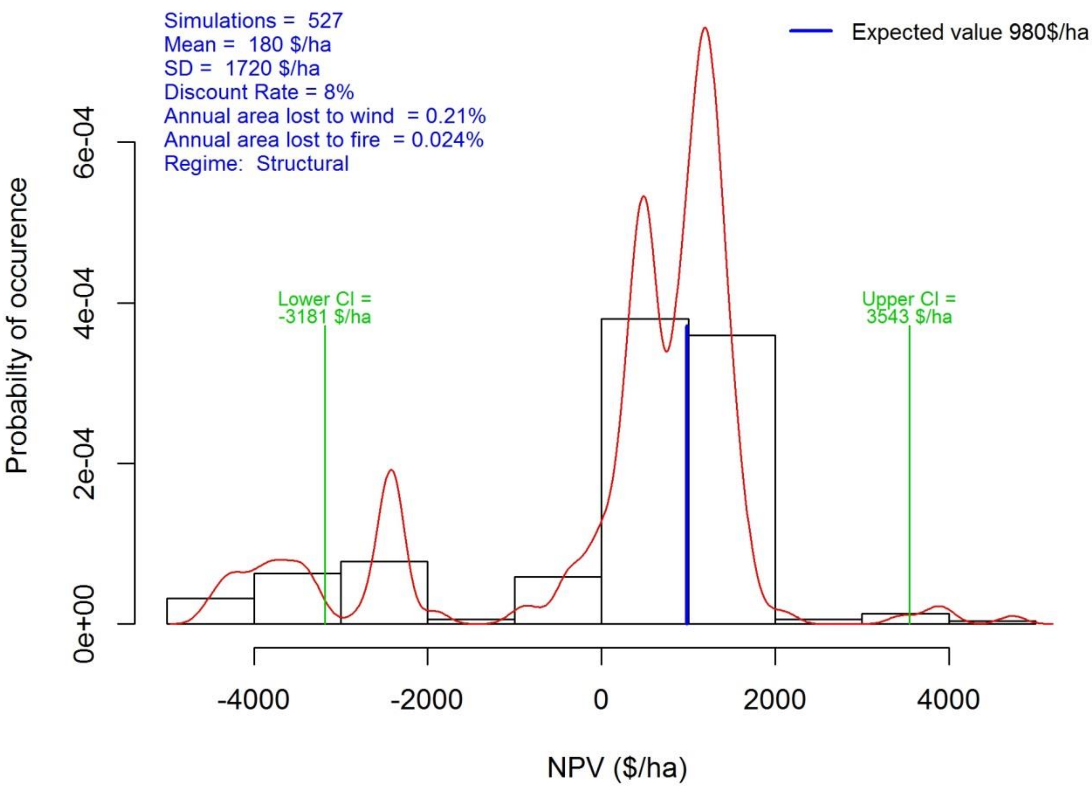


Figure 4-22: **Low productivity, with damage, appearance regime over 1,000ha: Net Present Value**

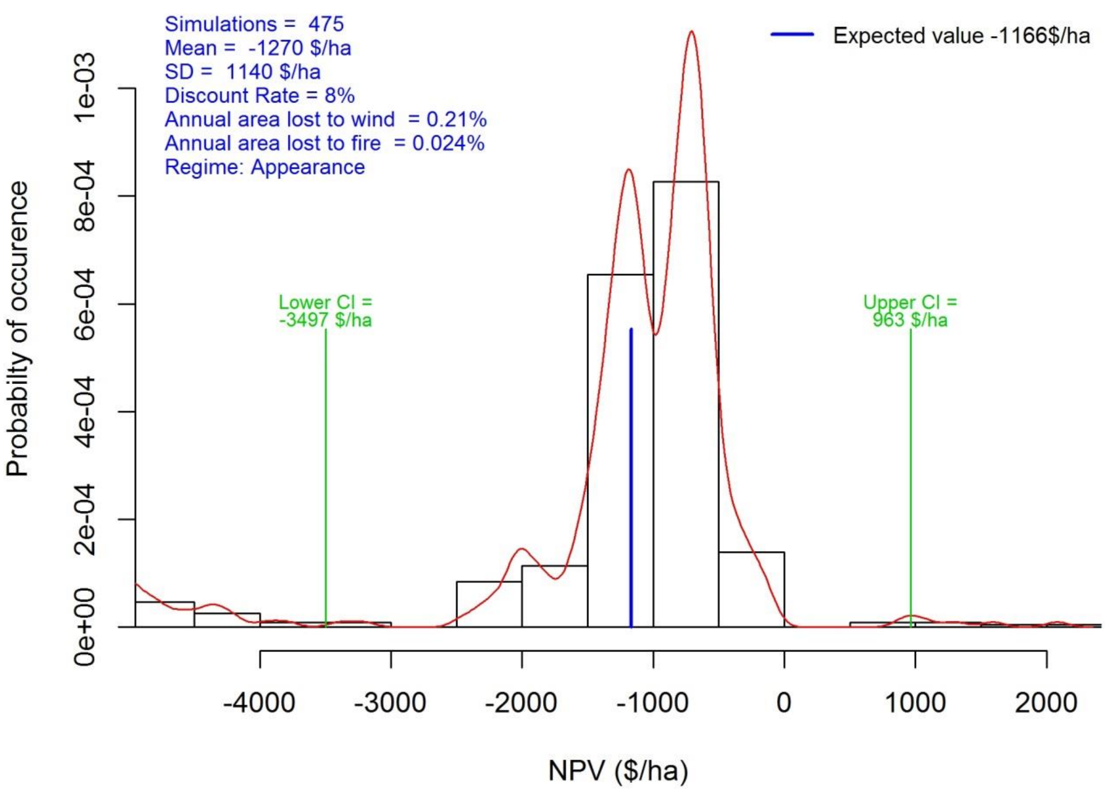


Figure 4-23: **High productivity, with damage, structural regime over 1,000ha:**
Net Present Value

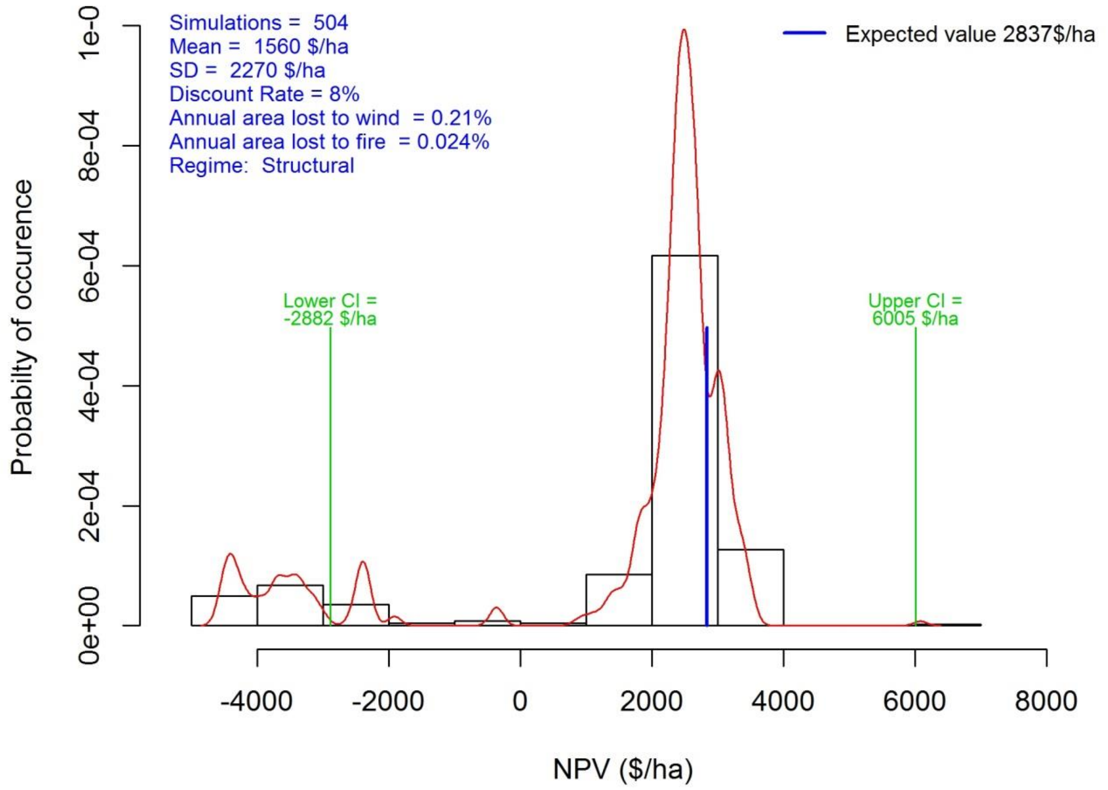
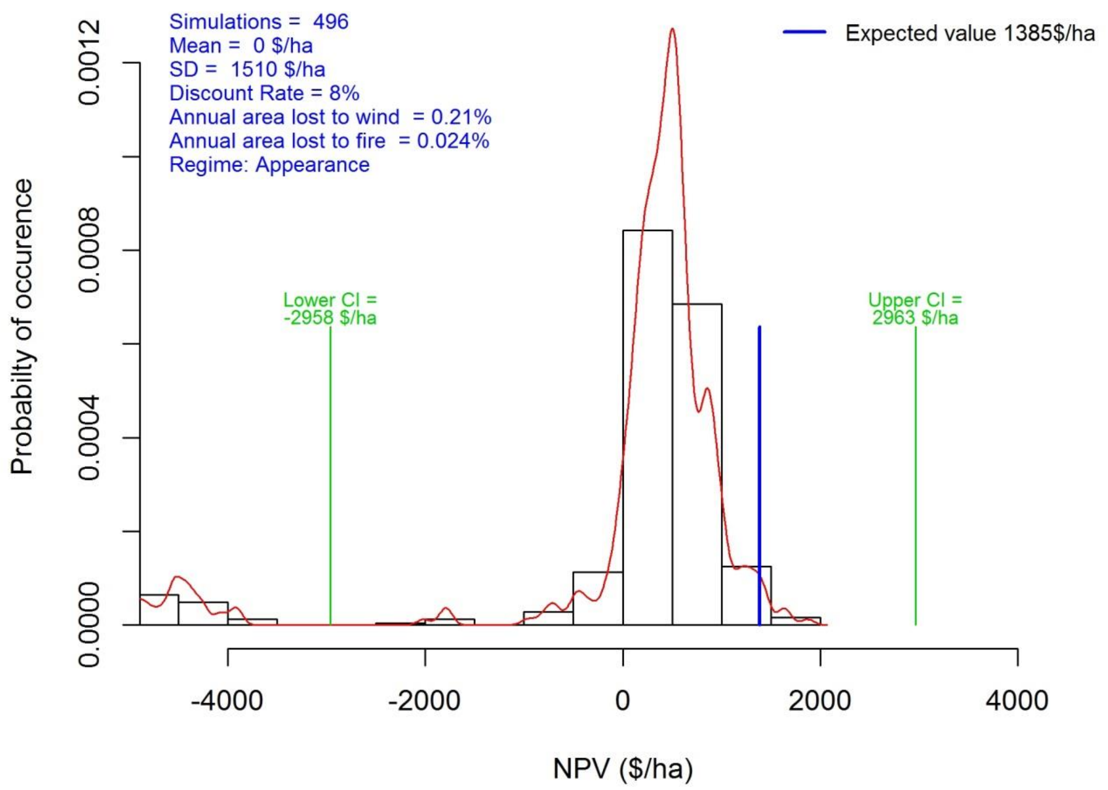


Figure 4-24: **High productivity, with damage, appearance regime over 1,000ha:**
Net Present Value



Discussion

The green crown length model shows a good fit to the case study forest data. The relationship with stocking and MTH are well represented and the residuals show an even spread. In combination with crown length crown width is used in the wind damage probability calculation. Crown width is calculated as the spacing between trees. This is based on the assumption that the forest has achieved crown closure. In the situation where probabilities are calculated before crown closure the crown width will have been over predicted. However, this may go some to addressing the effect of an open canopy, which the model would otherwise ignore. As discussed in chapter 2 – "Catastrophic damage" canopies are more susceptible to damage from wind when the canopy is open and the wind is able to get underneath.

The probability of windthrow shown shows the expected trend with a sharp increase in windthrow following silviculture, and an overall increasing probability of windthrow with age. The sharp increase in probability following silviculture is a direct result of the crown width model assessing tree spacing instead of true crown width, but this has captured a realistic increase in the probability in windthrow as the crown is opened up during the final thinning operation. There is some variation from the expected trend where many simulations have close to a zero probability right up to harvest, showing the approach utilising the difference between the resistive moment from the root system with the estimated moment created by the wind in the tree canopy calibrated to the regional probability of wind damage has some limitations.

Combining the productivity error prediction and reduction in productivity from forest growth gives useful information on the uncertainty associated with predicting forest growth. Taking the forest growth calculations through from carbon sequestration to NPVs increased the variance around the estimations significantly. Calculating NPVs used the timing of silviculture, timing of harvest and volume by log grade from the Forecaster growth modelling software. To calculate log grade volumes the software must consider the shape of the tree stems and size of the branches. A small change in productivity indices can result in a large shift in log grades as the change in growth can cause a significant portion of the resulting logs to move into the next log grade category. For example if a log changes from having a small end diameter of 399 to over 400 millimetres, it moves to the category for the largest logs, which is worth more per cubic metre. If this happens to a number of logs there is a significant change in log price paid per cubic metre amplifying the initial variation in productivity indices. For this reason there is a high degree of risk in new forest investments. This uncertainty is exacerbated if relying on carbon sequestration as a source of income before harvesting.

This model is set up to quantify the variation in carbon estimates and forest value due to variation in forest growth estimates and the effects of catastrophic damage from wind and fire. For this reason forestry costs and revenues are kept constant. Full stochastic forest modelling would provide the true confidence interval for NPV estimates, but would require stochastic processes in the model to generate these costs. This is outside the scope of this study, but due to the flexible nature of the R programming language could be built into the model for future studies. However, the findings of this study indicate the confidence intervals for full stochastic analysis of NPV would be very wide and the method not precise enough to render useful results.

This chapter has discussed the construction of the model, its performance and potential for further use. The remainder of the analysis is continued in the overall discussion section and conclusions in chapter five.

Conclusions

The intermediate models used to predict green crown length and crown width provide good estimates of crown parameters. The calculated moment applied by wind on the canopy calculated from tree crown parameters in combination with the formula for the resistive moment supplied by the tree crown from Moore and Quine (2000) and the regional probability of wind damage from Moore, Manley et al. (2011) are a useful way to apply wind damage in this stochastic modelling system.

Overall the modelling system provides a useful method to assess uncertainty in forest productivity predictions considering both forest productivity prediction error and potential catastrophic damage. The comparisons over site productivity, stand size and silviculture while not statistically significant provide useful insights into the uncertainty associated with forest investments for carbon sequestration and timber production.

Chapter 5 Disscussion

The model constructed for this research runs multiple simulations of forest growth with stochastically generated forest growth productivity indices and stochastic wind and fire damage processes to show the influence of these factors on uncertainty in estimates of carbon sequestered and value for potential new forest investors. The model has been calibrated using site productivity, stand size and damage from wind in case study forests in the Central North Island of New Zealand for forest growth, and in Canterbury in the South Island of New Zealand for wind and fire damage (as described in chapters two and three).

This modelling process incorporates error around the predicted site productivity as well as the variable reduction in forest volume from wind and fire damage. By combining both the error in productivity estimates and catastrophic damage all sources of variation are included in the overall combined model; both those sources of variation which reduce forest growth, and catastrophic damage which is severe enough that the forest can no longer maintain an economic tree crop. The distinction between abandoning or maintaining a tree crop for financial benefit aligns well with standard practice for abandoning PSP measurement following damage, where regular PSP are measurements are continued unless damage is sever enough to stop safe access to the PSP by measurement personnel or where continued measurement will provide non-representative forest growth data. Because of the alignment between when a tree crop is abandoned for financial reasons following damage and when a PSP is abandoned from future measurements the PSP data used for calculating prediction error of the productivity maps provided a convenient method to separate minor and catastrophic damage for this research.

The sources of catastrophic damage acknowledged in this model are wind and fire. Although biological sources of damage can be catastrophic with examples such as the mountain pine beetle in

Canada and the United States, there were no quantifiable cases of catastrophic biological damage in New Zealand to provide data for that to be included in the simulations. Key assumptions needed for building the model including sources of damage are based on information from the two case study forests in the Central North Island for productivity prediction error and in Canterbury for wind and fire damage.

The carbon sequestration estimates provide smaller confidence intervals without wind damage, however the more realistic simulations with wind damage included have confidence intervals around 20%, showing how wind damage adds to the uncertainty in carbon sequestration predictions. In addition to variation in predicted growth carbon credit prices in the ETS are highly variable, and are the biggest effect on variability to the returns to forest investors. Because of the uncertainty in forest growth prediction and volatile carbon pricing investing in forestry and relying on revenue from carbon sequestration is a high risk investment. The charts presented from this stochastic analysis provide useful information for a potential forest investor in the form of a distribution of possible carbon sequestration and value of returns in perpetuity for comparison with the deterministically calculated expected value.

For the national carbon reporting effort the variability in one stand is not of significance, as the national carbon balance will be summed across the country combining the carbon sequestration over a large number of stands. Any underperforming forests will be offset by those stands with high productivity in other areas. While the variability will not be significant the overall average reduction in carbon sequestration from wind and fire will reduce the overall national balance. This research indicates a reduction between 3% and 5% due to catastrophic windthrow rate of 0.21% annually and a catastrophic fire damage rate of 0.024% annually. These rates represent windthrow rates typical of a Central North Island forest and average rates of fire damage for New Zealand.

The effect of area in chapter1 – "Generating Productivity indices" showed that larger forest stands produced less variation in the productivity indices used to parameterise the growth rates in simulations. The carbon sequestration results for the larger area stands showed that in the growth modelling process any effect of the more condensed productivity indices for larger stands is lost in the forest growth modelling simulation before carbon sequestration is calculated.

The large variability in NPV estimations means that no significant effect of catastrophic damage could be identified. Across the eight NPV simulation sets the effect of including catastrophic wind and fire damage at a rate typical of a Central North Island forest generally reduced NPVs, with the decrease in mean values ranging from no change to a drop of $1200 per hectare. Because of the large variation in NPV estimates these results were not statistically significant. Despite the lack of statistical significance the charts presented is this study provide useful insights into the effects of productivity prediction uncertainty and variable reduction from wind damage. The form for both stochastically generated carbon sequestration and NPV estimates is a distribution around the expected value calculated with deterministic methods and a significant tail representing the simulations affected by catastrophic damage. For almost all NPV simulation sets the range of probably values included zero, showing that forest investment includes a certain level of risk.

Conclusions

Confidence intervals for estimates of carbon sequestration are around 10% of the mean estimation with no wind or fire damage. Simulations of carbon sequestration with wind damage included have confidence intervals around 20% of the mean estimation of carbon sequestered at harvest. There is a significant increase in variability due to the effects of wind and fire.

The simulations in this research indicate a reduction in carbon sequestered due to wind and fire of 5% for structural regimes and 3% for appearance regimes, based on a catastrophic windthrow rate of 0.24% annually and a catastrophic fire damage rate of 0.024% annually. These rates match the rate of catastrophic wind damage for a Central North Island forest (Moore, Manley et al. 2011) and average fire damage for New Zealand forests (Anderson, Doherty et al. 2008). This loss in volume generally translated to a reduction in NPV although there was a large range from no change to a drop of $1200 per hectare across the 8 simulated scenarios.

Forestry is a risky investment and the variance in predicted carbon sequestration means that sequestering carbon does not make forestry a reliable source of income to bridge the time period before log revenue at harvest for new forest investments. Stochastic analysis to quantify the possibilities for investment is useful to convey the possible outcomes to a potential investor, but does not provide statistically significant results to rely on for investment decisions.

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Appendix A: LENZ environment types in Kaingaroa Forest.

Kaingaroa Forest was mapped the Land Environments of New Zealand classes (Leathwick, Wilson et al. 2003). The following is a list of Level 4 LENZ environments found in Kaingaroa Forest:

LENZ Class F: Central Hill Country and Volcanic Plateau

F6.1

Location: Waikato and coastal Bay of Plenty
Climate: Mild temperatures, high solar radiation, low monthly water balance
Landform: Undulating hills
Soils: Well drained, low fertility soils from mid-age ryolitic tephra
F6.1b: cooler temperatures than above
F6.1c: cooler temperatures than above
F6.1e: average as per above

F 6.2

Location: Urewera Ranges
Climate: Mild temperatures, high solar radiation and no annual water deficits
Landform: Steep mountains
Soils: Well drained, low fertility soils from mid-age ryolitic tephra
F6.2a: average as per above

F 7.1

Location: Northeast Volcanic Plateau, surrounding Lake Taupo
Climate: Mild Temperatures, high solar radiation, slight annual water deficits
Landform: Undulating volcanic plateau
Soils: Well drained, very low fertility soils from rhyolitic flow tephra.
F7.1a: warmer temperatures than above
F7.1b: average as per above
F7.1c: lower temperatures than above

LENZ Class P: Central Mountains

P 7.1

Location: Northern end of the Ruahine range
Climate: Cool temperatures, high solar radiation, low vapour pressure deficits, low monthly water balance ratios, slight annual water deficits.
Landform: Steep mountainous terrain
Soils: Well drained soils of low natural fertility from ryolitic and andesic tephra with some greywake, agillite and sandstone.
P7.1b: warmer temperatures than above, weakly indurated, fine textured soils.